

This Page Is Inserted by IFW Operations  
and is not a part of the Official Record

## **BEST AVAILABLE IMAGES**

Defective images within this document are accurate representations of the original documents submitted by the applicant.

Defects in the images may include (but are not limited to):

- BLACK BORDERS
- TEXT CUT OFF AT TOP, BOTTOM OR SIDES
- FADED TEXT
- ILLEGIBLE TEXT
- SKEWED/SLANTED IMAGES
- COLORED PHOTOS
- BLACK OR VERY BLACK AND WHITE DARK PHOTOS
- GRAY SCALE DOCUMENTS

**IMAGES ARE BEST AVAILABLE COPY.**

**As rescanning documents *will not* correct images,  
please do not report the images to the  
Image Problem Mailbox.**



Docket No.: PF-0621 USN

**Response Under 37 C.F.R. 1.116 - Expedited Procedure**  
**Examining Group 1652**

Certificate of Mailing

I hereby certify that this correspondence is being deposited with the United States Postal Service as first class mail in an envelope addressed to:  
Mail Stop Appeal Brief-Patents, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450 on March 5, 2004.

By: [Signature]

Printed: Lisa McDill

**IN THE UNITED STATES PATENT AND TRADEMARK OFFICE**

In re Application of: Tang et al.

Title: MYOSIN HEAVY CHAIN HOMOLOG

Serial No.: 09/830,914

Filing Date: May 02, 2001

Examiner: Fronza, C.

Group Art Unit: 1652

Mail Stop Appeal Brief-Patents  
Commissioner for Patents  
P.O. Box 1450  
Alexandria, VA 22313-1450

**TRANSMITTAL FEE SHEET**

Sir:

Transmitted herewith are the following for the above-identified application:

1. Return Receipt Postcard;
2. Brief on Appeal, including Appendix (35 pp., in triplicate); and
3. Eight (8) References, as cited in Brief (1 - 8, in triplicate).

The fee has been calculated as shown below.

       No additional Fee is required.

  X   Fee for filing a Brief in support of an Appeal under 37 CFR 1.17(c): \$ 330.00

  X   Please charge Deposit Account No. 09-0108 in the amount of : \$ 330.00

The Commissioner is hereby authorized to charge any additional fees required under 37 CFR 1.16 and 1.17, or credit overpayment to Deposit Account No. 09-0108. **A duplicate copy of this sheet is enclosed.**

Respectfully submitted,

INCYTE CORPORATION

[Signature]

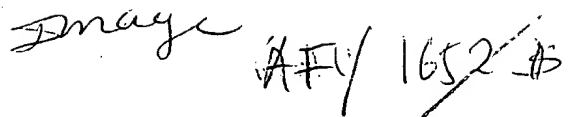
James M. Verna, Ph.D.

Reg. No. 33,287

Direct Dial Telephone: (650) 845-5415

Date: March 5, 2004

Customer No.: 27904  
3160 Porter Drive  
Palo Alto, California 94304  
Phone: (650) 855-0555  
Fax: (650) 845-4166



**Response Under 37 C.F.R. 1.116 - Expedited Procedure**  
**Examining Group 1652**

Whereby certify that this correspondence is being deposited with the United States Postal Service as first class mail in an envelope addressed to: Mail Stop Appeal Brief-Patents, Commissioner for Patents, P.O. Box 1450, Alexandria, VA 22313-1450 on March 5, 2004.

Printed: Lisa McDill

In re Application of: Tang et al.

Group Art Unit: 1652

# BRIEF ON APPEAL

Further to the Notice of Appeal filed January 2, 2003, and received by the USPTO on January 5, 2003, herewith are three copies of Appellants' Brief on Appeal. Authorized fees include the \$ **330.00** fee for the filing of this Brief.

This is an appeal from the decision of the Examiner finally rejecting claims 23-31 of the above-identified application.

(1) REAL PARTY IN INTEREST

The above-identified application is assigned of record to **Incyte Pharmaceuticals, Inc., (now Incyte Corporation, formerly known as Incyte Genomics, Inc. )** (Reel 012552, Frame 0584) which is the real party in interest herein.

01 FC:1402 330.00 DA

(2) RELATED APPEALS AND INTERFERENCES

Appellants, their legal representative and the assignee are not aware of any related appeals or interferences which will directly affect or be directly affected by or have a bearing on the Board's decision in the instant appeal.

(3) STATUS OF THE CLAIMS

Claims rejected:	Claims 23-31
Claims allowed:	(none)
Claims canceled:	Claims 1-22
Claims withdrawn:	Claims 32-40
Claims on Appeal:	Claims 23-31 (A copy of the claims on appeal, as amended, can be found in the attached Appendix).

(4) STATUS OF AMENDMENTS AFTER FINAL

**The Amendment after Final Rejection under 37 C.F.R. §1.116 filed December 2, 2003 has been entered for purposes of this appeal.**

(5) SUMMARY OF THE INVENTION

Appellants' invention is directed to polynucleotides comprising the polynucleotide sequence of SEQ ID NO:2, encoding the human myosin heavy chain homolog (MHCH), comprising the amino acid sequence of SEQ ID NO:1 (Specification, e.g., at page 2, lines 28-30 and page 3, lines 12-13). Appellants' invention also includes polynucleotides comprising a naturally occurring polynucleotide sequence at least 70% identical to a polynucleotide sequence of SEQ ID NO:2, and polynucleotides encoding a polypeptide comprising a naturally occurring amino acid sequence at least 90% identical to an amino acid sequence of SEQ ID NO:1, said polypeptide having ATPase activity, (e.g., at page 2, lines 30-33; page 3, lines 14-16; page 17, lines 8-13; and page 18, lines 18-33), polynucleotides encoding biologically active fragments of SEQ ID NO:1, complementary polynucleotides (e.g., at page 3, lines 2-5 and 12-13; and page 7, lines 4-5), recombinant polynucleotides encoding polypeptides comprising SEQ ID NO:1, variants, or fragments thereof (e.g., at page 3, lines 19-22), host cells transformed with recombinant



polynucleotides, and methods of making polypeptides encoded by the claimed polynucleotides (e.g., at page 3, lines 21-26; pages 22-25; and Example IX at pages 47-48; and Example XIII at page 50).

MHCH has chemical and structural homology to Caenorhabditis elegans myosin I heavy chain (GI 1279777; SEQ ID NO:3), and Helianthus annuus unconventional myosin I heavy chain (GI 2444174; SEQ ID NO:4). For example:

MHCH is 612 amino acids in length and has 7 potential casein kinase II phosphorylation sites at residues S62, T146, T221, S280, S323, S390, and T546, and 6 potential protein kinase C phosphorylation sites at residues S19, S140, S303, T441, S555, and S563. The sequence from T383 through M387 of MHCH is 80% identical to the conserved sequence found at the end of myosin head domains. MHCH contains two possible light-chain binding sites. The first, from I410 through E421, contains 4 out of 6 conserved residues and the second, from I432 through K443, contains 5 out of 6 conserved residues. PFAM analysis shows that MHCH shares homology with a myosin head domain from residue F51 to residue L314. PRINTS analysis shows that MHCH shares homology with a myosin heavy chain signature motif from residue F51 to K79 and from residue F105 to C133. MHCH has a possible transmembrane motif from residue W506 to P535. As shown in Figures 2A, 2B, 2C, 2D, 2E, 2F, 2G, 2H, 2I, 2J and 2K, MHCH has chemical and structural similarity with Caenorhabditis elegans myosin I heavy chain (GI 1279777; SEQ ID NO:3), and Helianthus annuus unconventional myosin heavy chain (GI 2444174; SEQ ID NO:4). MHCH and myosin I heavy chain share 23.2% identity, and in particular they share 39% identity from residue F51 to residue L314. MHCH and unconventional myosin I share 22.4% identity, and in particular they share 38% identity from residue F51 to residue L314 of MHCH. (Specification, page 17, line 27 to page 18, line 9).

The polynucleotides of the present invention are useful, for example, for toxicology testing, drug discovery, and diagnosis, prevention, and treatment of heart and skeletal muscle disorders, developmental disorders, and cell proliferative disorders, including cancer.

## (6) ISSUES

1. Whether claims 23-31 directed to polynucleotides encoding MHCH sequences meet the utility requirement of 35 U.S.C. §101.
2. Whether one of ordinary skill in the art would know how to use the claimed

sequences, e.g., in toxicology testing, drug development, and the diagnosis of disease, so as to satisfy the enablement requirement of 35 U.S.C. §112, first paragraph.

3. Whether one of ordinary skill in the art would know how to make the claimed polynucleotide variants and fragments according to claims 23, 26-28, and 30, so as to satisfy the enablement requirement of 35 U.S.C. §112, first paragraph.

4. Whether claims 23, 26-28, 30, and 31 meet the written description requirement of 35 U.S.C. §112, first paragraph.

**(7) GROUPING OF THE CLAIMS**

**As to Issue 1**

All of the claims on appeal are grouped together.

**As to Issue 2**

All of the claims on appeal are grouped together.

**As to Issue 3**

All of the claims on appeal are grouped together.

**As to Issue 4**

All of the claims on appeal are grouped together.

**(8) APPELLANTS' ARGUMENTS**

**Issue 1 – Whether the claims meet the utility requirement of 35 U.S.C. § 101**

**The rejection of claims 23-31 is improper, as the inventions of those claims have a patentable utility as set forth in the instant specification, and/or a utility well known to one of ordinary skill in the art.**

The invention at issue is a polynucleotide sequence corresponding to a gene that is expressed in hematopoietic/immune system, gastrointestinal, musculoskeletal, and reproductive tissues, and in tissues associated with cancer (Specification at page 18, lines 12-17). In particular, similarities between SEQ ID NO:1 and *C. elegans* myosin (g1279777) and *H. annuus*

unconventional myosin (g2444174), including the presence of myosin head domain, myosin heavy chain, and light chain binding site signatures, are described in the specification, for example, at page 17, line 30 through page 18, line 9. The specification points out the roles of myosin in muscle contraction, intracellular movement, phagocytosis, and cytokinesis, and describes various diseases associated with myosin dysfunction, including muscle disorders, cardiovascular disease, deafness, and cancer (Specification at pages 1-2). As such, the claimed invention has numerous practical, beneficial uses in toxicology testing, drug development, and the diagnosis of disease, none of which requires knowledge of how the polypeptide coded for by the polynucleotide actually functions.

Appellants previously submitted the Declaration of Dr. Tod Bedilion describing some of the practical uses of the claimed invention in gene and protein expression monitoring applications. The Bedilion Declaration demonstrates that the positions and arguments made by the Patent Examiner with respect to the utility of the claimed polynucleotide are without merit.

The Bedilion Declaration describes, in particular, how the claimed expressed polynucleotide can be used in gene expression monitoring applications that were well-known at the time the patent application was filed, and how those applications are useful in developing drugs and monitoring their activity. Dr. Bedilion states that the claimed invention is a useful tool when employed as a highly specific probe in a cDNA microarray:

Persons skilled in the art would appreciate that cDNA microarrays that contained the SEQ ID NO:1-encoding polynucleotides would be a more useful tool than cDNA microarrays that did not contain the polynucleotides in connection with conducting gene expression monitoring studies on proposed (or actual) drugs for treating heart and skeletal muscle disorders, developmental disorders, and cell proliferative disorders, including cancer for such purposes as evaluating their efficacy and toxicity.

The Patent Examiner does not dispute that the claimed polynucleotide can be used as a probe in cDNA microarrays and used in gene expression monitoring applications. Instead, the Patent Examiner contends that the claimed polynucleotide cannot be useful without precise knowledge of its biological function. But the law never has required knowledge of biological function to prove utility. It is the claimed invention's uses, not its functions, that are the subject of a proper analysis under the utility requirement.

In any event, as demonstrated by the Bedilion Declaration, the person of ordinary skill in the art can achieve beneficial results from the claimed polynucleotide in the absence of any knowledge as to the precise function of the protein encoded by it. The uses of the claimed polynucleotide in gene expression monitoring applications are in fact independent of its precise function.

## **I. The Applicable Legal Standard**

To meet the utility requirement of sections 101 and 112 of the Patent Act, the patent applicant need only show that the claimed invention is “practically useful,” *Anderson v. Natta*, 480 F.2d 1392, 1397, 178 USPQ 458 (CCPA 1973) and confers a “specific benefit” on the public. *Brenner v. Manson*, 383 U.S. 519, 534-35, 148 USPQ 689 (1966). As discussed in a recent Court of Appeals for the Federal Circuit case, this threshold is not high:

An invention is “useful” under section 101 if it is capable of providing some identifiable benefit. See *Brenner v. Manson*, 383 U.S. 519, 534 [148 USPQ 689] (1966); *Brooktree Corp. v. Advanced Micro Devices, Inc.*, 977 F.2d 1555, 1571 [24 USPQ2d 1401] (Fed. Cir. 1992) (“to violate Section 101 the claimed device must be totally incapable of achieving a useful result”); *Fuller v. Berger*, 120 F. 274, 275 (7th Cir. 1903) (test for utility is whether invention “is incapable of serving any beneficial end”).

*Juicy Whip Inc. v. Orange Bang Inc.*, 51 USPQ2d 1700 (Fed. Cir. 1999).

While an asserted utility must be described with specificity, the patent applicant need not demonstrate utility to a certainty. In *Stiftung v. Renishaw PLC*, 945 F.2d 1173, 1180, 20 USPQ2d 1094 (Fed. Cir. 1991), the United States Court of Appeals for the Federal Circuit explained:

An invention need not be the best or only way to accomplish a certain result, and it need only be useful to some extent and in certain applications: “[T]he fact that an invention has only limited utility and is only operable in certain applications is not grounds for finding lack of utility.” *Envirotech Corp. v. Al George, Inc.*, 730 F.2d 753, 762, 221 USPQ 473, 480 (Fed. Cir. 1984).

The specificity requirement is not, therefore, an onerous one. If the asserted utility is described so that a person of ordinary skill in the art would understand how to use the claimed invention, it is sufficiently specific. See *Standard Oil Co. v. Montedison, S.p.a.*, 212 U.S.P.Q. 327, 343 (3d Cir. 1981). The specificity requirement is met unless the asserted utility amounts to a “nebulous expression” such as “biological activity” or “biological properties” that does not

convey meaningful information about the utility of what is being claimed. *Cross v. Iizuka*, 753 F.2d 1040, 1048 (Fed. Cir. 1985).

In addition to conferring a specific benefit on the public, the benefit must also be “substantial.” *Brenner*, 383 U.S. at 534. A “substantial” utility is a practical, “real-world” utility. *Nelson v. Bowler*, 626 F.2d 853, 856, 206 USPQ 881 (CCPA 1980).

If persons of ordinary skill in the art would understand that there is a “well-established” utility for the claimed invention, the threshold is met automatically and the applicant need not make any showing to demonstrate utility. Manual of Patent Examination Procedure at § 706.03(a). Only if there is no “well-established” utility for the claimed invention must the applicant demonstrate the practical benefits of the invention. *Id.*

Once the patent applicant identifies a specific utility, the claimed invention is presumed to possess it. *In re Cortright*, 165 F.3d 1353, 1357, 49 USPQ2d 1464 (Fed. Cir. 1999); *In re Brana*, 51 F.3d 1560, 1566; 34 USPQ2d 1436 (Fed. Cir. 1995). In that case, the Patent Office bears the burden of demonstrating that a person of ordinary skill in the art would reasonably doubt that the asserted utility could be achieved by the claimed invention. *Id.* To do so, the Patent Office must provide evidence or sound scientific reasoning. See *In re Langer*, 503 F.2d 1380, 1391-92, 183 USPQ 288 (CCPA 1974). If and only if the Patent Office makes such a showing, the burden shifts to the applicant to provide rebuttal evidence that would convince the person of ordinary skill that there is sufficient proof of utility. *Brana*, 51 F.3d at 1566. The applicant need only prove a “substantial likelihood” of utility; certainty is not required. *Brenner*, 383 U.S. at 532.

**II. Use of the claimed polynucleotide for diagnosis of conditions or diseases characterized by expression of MHCH, for toxicology testing, and for drug discovery are sufficient utilities under 35 U.S.C. §§ 101 and 112, first paragraph**

The claimed invention meets all of the necessary requirements for establishing a credible utility under the Patent Law: There are “well-established” uses for the claimed invention known to persons of ordinary skill in the art, and there are specific practical and beneficial uses for the invention disclosed in the patent application’s specification. These uses are explained, in detail,

in the Bedilion Declaration previously submitted on July 7, 2003. Objective evidence, not considered by the Patent Office, further corroborates the credibility of the asserted utilities.

**A. The use of MHCH for toxicology testing, drug discovery, and disease diagnosis are practical uses that confer “specific benefits” to the public**

The claimed invention has specific, substantial, real-world utility by virtue of its use in toxicology testing, drug development and disease diagnosis through gene expression profiling. These uses are explained in detail in the accompanying Bedilion Declaration, the substance of which is not rebutted by the Patent Examiner. There is no dispute that the claimed invention is in fact a useful tool in cDNA microarrays used to perform gene expression analysis. That is sufficient to establish utility for the claimed polynucleotide.

In his Declaration, Dr. Bedilion explains the many reasons why a person skilled in the art reading the Tang ‘248 application on November 5, 1998 would have understood that application to disclose the claimed polynucleotide to be useful for a number of gene expression monitoring applications, *e.g.*, as a highly specific probe for the expression of that specific polynucleotide in connection with the development of drugs and the monitoring of the activity of such drugs. (Bedilion Declaration at, *e.g.*, ¶¶ 10-15). Much, but not all, of Dr. Bedilion’s explanation concerns the use of the claimed polynucleotide in cDNA microarrays of the type first developed at Stanford University for evaluating the efficacy and toxicity of drugs, as well as for other applications. (Bedilion Declaration, ¶¶ 12 and 15).<sup>1</sup>

In connection with his explanations, Dr. Bedilion states that the “Tang ‘248 specification would have led a person skilled in the art on November 5, 1998 who was using gene expression monitoring in connection with working on developing new drugs for the treatment of heart and skeletal muscle disorders, developmental disorders, and cell proliferative disorders, including cancer [a] to conclude that a cDNA microarray that contained the SEQ ID NO:1-encoding polynucleotides would be a highly useful tool, and [b] to request specifically that any cDNA microarray that was being used for such purposes contain the SEQ ID NO:1-encoding

---

<sup>1</sup>Dr. Bedilion also explained, for example, why persons skilled in the art would also appreciate, based on the Tang ‘248 specification, that the claimed polynucleotide would be useful in connection with developing new drugs using technology, such as Northern analysis, that predated by many years the development of the cDNA technology (Bedilion Declaration, ¶ 16).

polynucleotides” (Bedilion Declaration, ¶ 15 ). For example, as explained by Dr. Bedilion, “[p]ersons skilled in the art would [have appreciated on November 5, 1998] that a cDNA microarray that contained the SEQ ID NO:1-encoding polynucleotides would be a more useful tool than a cDNA microarray that did not contain the polynucleotides in connection with conducting gene expression monitoring studies on proposed (or actual) drugs for treating heart and skeletal muscle disorders, developmental disorders, and cell proliferative disorders, including cancer for such purposes as evaluating their efficacy and toxicity.” *Id.*

In support of those statements, Dr. Bedilion provided detailed explanations of how cDNA technology can be used to conduct gene expression monitoring evaluations, with extensive citations to pre-November 5, 1998 publications showing the state of the art on November 5, 1998. (Bedilion Declaration, ¶¶ 10-14). While Dr. Bedilion’s explanations in paragraph 15 of his Declaration include almost three pages of text and six subparts (a)-(f), he specifically states that his explanations are not “all-inclusive.” *Id.* For example, with respect to toxicity evaluations, Dr. Bedilion had earlier explained how persons skilled in the art who were working on drug development on November 5, 1998 (and for several years prior to November 5, 1998) “without any doubt” appreciated that the toxicity (or lack of toxicity) of any proposed drug was “one of the most important criteria to be evaluated in connection with the development of the drug” and how the teachings of the Tang ‘248 application clearly include using differential gene expression analyses in toxicity studies (Bedilion Declaration, ¶ 10).

Thus, the Bedilion Declaration establishes that persons skilled in the art reading the Tang ‘248 application at the time it was filed “would have wanted their cDNA microarray to have a [SEQ ID NO:1-encoding polynucleotide probe] because a microarray that contained such a probe (as compared to one that did not) would provide more useful results in the kind of gene expression monitoring studies using cDNA microarrays that persons skilled in the art have been doing since well prior to November 5, 1998” (Bedilion Declaration, ¶ 15, item (f)). This, by itself, provides more than sufficient reason to compel the conclusion that the Tang ‘248 application disclosed to persons skilled in the art at the time of its filing substantial, specific and credible real-world utilities for the claimed polynucleotide.

Nowhere does the Patent Examiner address the fact that, as described on pp. 31-32 of the Tang ‘248 application, the claimed polynucleotides can be used as highly specific probes in, for

example, cDNA microarrays – probes that without question can be used to measure both the existence and amount of complementary RNA sequences known to be the expression products of the claimed polynucleotides. The claimed invention is not, in that regard, some random sequence whose value as a probe is speculative or would require further research to determine.

Given the fact that the claimed polynucleotide is known to be expressed, its utility as a measuring and analyzing instrument for expression levels is as indisputable as a scale's utility for measuring weight. This use as a measuring tool, regardless of how the expression level data ultimately would be used by a person of ordinary skill in the art, by itself demonstrates that the claimed invention provides an identifiable, real-world benefit that meets the utility requirement. *Raytheon v. Roper*, 724 F.2d 951, (Fed. Cir. 1983) (claimed invention need only meet one of its stated objectives to be useful); *In re Cortwright*, 165 F.3d 1353, 1359 (Fed. Cir. 1999) (how the invention works is irrelevant to utility); MPEP § 2107 (“Many research tools such as gas chromatographs, screening assays, and nucleotide sequencing techniques have a clear, specific, and unquestionable utility (e.g., they are useful in analyzing compounds)” (emphasis added)).

Though Appellants need not so prove to demonstrate utility, there can be no reasonable dispute that persons of ordinary skill in the art have numerous uses for information about relative gene expression including, for example, understanding the effects of a potential drug for treating heart and skeletal muscle disorders, developmental disorders, and cell proliferative disorders, including cancer. Because the patent application states explicitly that the claimed polynucleotide is known to be expressed in hematopoietic/immune system, gastrointestinal, musculoskeletal, and reproductive tissues, and in tissues associated with cancer (Specification at page 18, lines 12-17), and expresses a protein that is a member of the myosin family known to be associated with diseases such as heart and skeletal muscle disorders, developmental disorders, and cell proliferative disorders, including cancer, there can be no reasonable dispute that a person of ordinary skill in the art could put the claimed invention to such use. In other words, the person of ordinary skill in the art can derive more information about a potential heart and skeletal muscle disorders, developmental disorders, and cell proliferative disorders, including cancer drug candidate or potential toxin with the claimed invention than without it (see Bedilion Declaration at, e.g., ¶ 15, subparts (e)-(f)).



The Bedilion Declaration shows that a number of pre-November 5, 1998 publications confirm and further establish the utility of cDNA microarrays in a wide range of drug development gene expression monitoring applications at the time the Tang '248 application was filed (Bedilion Declaration ¶¶ 10-14; Bedilion Exhibits A-G). Indeed, Brown and Shalon U.S. Patent No. 5,807,522 (the Brown '522 patent, Bedilion Exhibit D), which issued from a patent application filed in June 1995 and was effectively published on December 29, 1995 as a result of the publication of a PCT counterpart application, shows that the Patent Office recognizes the patentable utility of the cDNA technology developed in the early to mid-1990s. As explained by Dr. Bedilion, among other things (Bedilion Declaration, ¶ 12):

The Brown '522 patent further teaches that the "[m]icroarrays of immobilized nucleic acid sequences prepared in accordance with the invention" can be used in "numerous" genetic applications, including "monitoring of gene expression" applications (see Bedilion Tab D at col. 14, lines 36-42). The Brown '522 patent teaches (a) monitoring gene expression (i) in different tissue types, (ii) in different disease states, and (iii) in response to different drugs, and (b) that arrays disclosed therein may be used in toxicology studies (see Bedilion Tab D at col. 15, lines 13-18 and 52-58 and col. 18, lines 25-30).

Literature reviews published shortly after the filing of the Tang '248 application describing the state of the art further confirm the claimed invention's utility. Rockett et al. confirm, for example, that the claimed invention is useful for differential expression analysis regardless of how expression is regulated:

Despite the development of multiple technological advances which have recently brought the field of gene expression profiling to the forefront of molecular analysis, recognition of the importance of differential gene expression and characterization of differentially expressed genes has existed for many years.

\* \* \*

Although differential expression technologies are applicable to a broad range of models, perhaps their most important advantage is that, in most cases, absolutely no prior knowledge of the specific genes which are up- or down-regulated is required.

\* \* \*

Whereas it would be informative to know the identity and functionality of all genes up/down regulated by . . . toxicants, this would appear a longer term goal

.... However, the current use of gene profiling yields a *pattern* of gene changes for a xenobiotic of unknown toxicity which may be matched to that of well characterized toxins, thus alerting the toxicologist to possible *in vivo* similarities between the unknown and the standard, thereby providing a platform for more extensive toxicological examination. (emphasis added)

Rockett et al., Differential gene expression in drug metabolism and toxicology: practicalities, problems and potential, 29 Xenobiotica No. 7, 655 (1999).

In another pre-November 5, 1998 article, Lashkari et al. state explicitly that sequences that are merely “predicted” to be expressed (predicted Open Reading Frames, or ORFs) – the claimed invention in fact is known to be expressed – have numerous uses:

Efforts have been directed toward the amplification of each predicted ORF or any other region of the genome ranging from a few base pairs to several kilobase pairs. There are many uses for these amplicons– they can be cloned into standard vectors or specialized expression vectors, or can be cloned into other specialized vectors such as those used for two-hybrid analysis. The amplicons can also be used directly by, for example, arraying onto glass for expression analysis, for DNA binding assays, or for any direct DNA assay.

Lashkari et al., Whole genome analysis: Experimental access to all genome sequenced segments through larger-scale efficient oligonucleotide synthesis and PCR, 94 Proc. Nat. Acad. Sci. 8945 (Aug. 1997) (emphasis added).

**B. The use of nucleic acids coding for proteins expressed by humans as tools for toxicology testing, drug discovery, and the diagnosis of disease is now “well-established”**

The technologies made possible by expression profiling and the DNA tools upon which they rely are now well-established. The technical literature recognizes not only the prevalence of these technologies, but also their unprecedented advantages in drug development, testing and safety assessment. These technologies include toxicology testing, as described by Bedilion in his Declaration.

Toxicology testing is now standard practice in the pharmaceutical industry. See, e.g., John C. Rockett et al., *supra*:

Knowledge of toxin-dependent regulation in target tissues is not solely an academic pursuit as much interest has been generated in the pharmaceutical industry to harness this technology in the early identification of toxic drug candidates, thereby shortening the

developmental process and contributing substantially to the safety assessment of new drugs.

To the same effect are several other scientific publications, including Emile F. Nuwaysir et al., Microarrays and Toxicology: The Advent of Toxicogenomics, 24 Molecular Carcinogenesis 153 (1999); Sandra Steiner and N. Leigh Anderson, Expression profiling in toxicology -- potentials and limitations, 112-13 Toxicology Letters 467 (2000).

Nucleic acids useful for measuring the expression of whole classes of genes are routinely incorporated for use in toxicology testing. Nuwaysir et al. describes, for example, a Human ToxChip comprising 2089 human clones, which were selected

for their well-documented involvement in basic cellular processes as well as their responses to different types of toxic insult. Included on this list are DNA replication and repair genes, apoptosis genes, and genes responsive to PAHs and dioxin-like compounds, peroxisome proliferators, estrogenic compounds, and oxidant stress. Some of the other categories of genes include transcription factors, oncogenes, tumor suppressor genes, cyclins, kinases, phosphatases, cell adhesion and motility genes, and homeobox genes. Also included in this group are 84 housekeeping genes, whose hybridization intensity is averaged and used for signal normalization of the other genes on the chip.

See also Table 1 of Nuwaysir et al. (listing additional classes of genes deemed to be of special interest in making a human toxicology microarray).

The more genes that are available for use in toxicology testing, the more powerful the technique. "Arrays are at their most powerful when they contain the entire genome of the species they are being used to study." John C. Rockett and David J. Dix, Application of DNA Arrays to Toxicology, 107 Environ. Health Perspec. 681, No. 8 (1999). Control genes are carefully selected for their stability across a large set of array experiments in order to best study the effect of toxicological compounds. See attached email from the primary investigator on the Nuwaysir paper, Dr. Cynthia Afshari, to an Incyte employee, dated July 3, 2000, as well as the original message to which she was responding, indicating that even the expression of carefully selected control genes can be altered. Thus, there is no expressed gene which is irrelevant to screening for toxicological effects, and all expressed genes have a utility for toxicological screening.

In fact, the potential benefit to the public, in terms of lives saved and reduced health care costs, are enormous. Recent developments provide evidence that the benefits of this information are already beginning to manifest themselves. Examples include the following:

- In 1999, CV Therapeutics, an Incyte collaborator, was able to use Incyte gene expression technology, information about the structure of a known transporter gene, and chromosomal mapping location, to identify the key gene associated with Tangiers disease. This discovery took place over a matter of only a few weeks, due to the power of these new genomics technologies. The discovery received an award from the American Heart Association as one of the top 10 discoveries associated with heart disease research in 1999.
- In an April 9, 2000, article published by the Bloomberg news service, an Incyte customer stated that it had reduced the time associated with target discovery and validation from 36 months to 18 months, through use of Incyte's genomic information database. Other Incyte customers have privately reported similar experiences. The implications of this significant saving of time and expense for the number of drugs that may be developed and their cost are obvious.
- In a February 10, 2000, article in the *Wall Street Journal*, one Incyte customer stated that over 50 percent of the drug targets in its current pipeline were derived from the Incyte database. Other Incyte customers have privately reported similar experiences. By doubling the number of targets available to pharmaceutical researchers, Incyte genomic information has demonstrably accelerated the development of new drugs.

Because the Patent Examiner failed to address or consider the "well-established" utilities for the claimed invention in toxicology testing, drug development, and the diagnosis of disease, the Examiner's rejections should be overturned regardless of their merit.

**C. The Uncontested Fact That the Claimed Polynucleotide Encodes for a Protein in the Myosin Family Also Demonstrates Utility**

In addition to having substantial, specific and credible utilities in numerous gene expression monitoring applications, it is undisputed that the claimed polynucleotide encodes for a protein having the sequence shown as SEQ ID NO:1 in the patent application and referred to as MHCH in that application. Appellants have demonstrated that MHCH is a member of the myosin family, and that the myosin family of proteins includes motor proteins that are involved in muscle contraction, intracellular movement, phagocytosis, and cytokinesis.

The Patent Examiner does not dispute any of the facts set forth in the previous paragraph. Neither does the Patent Examiner dispute that, if a polynucleotide encodes for a protein that has a

substantial, specific and credible utility, then it follows that the polynucleotide also has a substantial, specific and credible utility.

The Examiner must accept the Appellant's demonstration that the polypeptide encoded by the claimed invention is a member of the myosin family and that utility is proven by a reasonable probability unless the Examiner can demonstrate through evidence or sound scientific reasoning that a person of ordinary skill in the art would doubt utility. *See In re Langer*, 503 F.2d 1380, 1391-92, 183 USPQ 288 (CCPA 1974). The Examiner has not provided sufficient evidence or sound scientific reasoning to the contrary.

Nor has the Examiner provided any evidence that any member of the myosin family, let alone a substantial number of those members, is not useful. In such circumstances, the only reasonable inference is that the polypeptide encoded by the claimed invention must be useful, like the other members of the myosin family.

**D. Objective evidence corroborates the utilities of the claimed invention**

There is, in fact, no restriction on the kinds of evidence a Patent Examiner may consider in determining whether a "real-world" utility exists. Indeed, "real-world" evidence, such as evidence showing actual use or commercial success of the invention, can demonstrate conclusive proof of utility. *Raytheon v. Roper*, 220 USPQ2d 592 (Fed. Cir. 1983); *Nestle v. Eugene*, 55 F.2d 854, 856, 12 USPQ 335 (6th Cir. 1932). Indeed, proof that the invention is made, used or sold by any person or entity other than the patentee is conclusive proof of utility. *United States Steel Corp. v. Phillips Petroleum Co.*, 865 F.2d 1247, 1252, 9 USPQ2d 1461 (Fed. Cir. 1989).

Over the past several years, a vibrant market has developed for databases containing all expressed genes (along with the polypeptide translations of those genes), in particular genes having medical and pharmaceutical significance such as the instant sequence. (Note that the value in these databases is enhanced by their completeness, but each sequence in them is independently valuable.) The databases sold by Appellants' assignee, Incyte, include exactly the kinds of information made possible by the claimed invention, such as tissue and disease associations. Incyte sells its database containing the claimed sequence and millions of other sequences throughout the scientific community, including to pharmaceutical companies who use the information to develop new pharmaceuticals.

Both Incyte's customers and the scientific community have acknowledged that Incyte's databases have proven to be valuable in, for example, the identification and development of drug candidates. As Incyte adds information to its databases, including the information that can be generated only as a result of Incyte's discovery of the claimed polynucleotide and its use of that polynucleotide on cDNA microarrays, the databases become even more powerful tools. Thus the claimed invention adds more than incremental benefit to the drug discovery and development process.

### **III. The Patent Examiner's Rejections Are Without Merit**

Rather than responding to the evidence demonstrating utility, the Examiner attempts to dismiss it altogether by arguing that the disclosed and well-established utilities for the claimed polynucleotide are not "specific or substantial" utilities. (Office Action at p. 4). The Examiner is incorrect both as a matter of law and as a matter of fact.

#### **A. The Precise Biological Role Or Function Of An Expressed Polynucleotide Is Not Required To Demonstrate Utility**

The Patent Examiner's primary rejection of the claimed invention is based on the ground that, without information as to the precise "biological role" of the claimed invention, the claimed invention's utility is not sufficiently specific. According to the Examiner, it is not enough that a person of ordinary skill in the art could use and, in fact, would want to use the claimed invention either by itself or in a cDNA microarray to monitor the expression of genes for such applications as the evaluation of a drug's efficacy and toxicity. The Examiner would require, in addition, that the Appellant provide a specific and substantial interpretation of the results generated in any given expression analysis.

It may be that specific and substantial interpretations and detailed information on biological function are necessary to satisfy the requirements for publication in some technical journals, but they are not necessary to satisfy the requirements for obtaining a United States patent. The relevant question is not, as the Examiner would have it, whether it is known how or why the invention works, *In re Cortwright*, 165 F.3d 1353, 1359 (Fed. Cir. 1999), but rather whether the invention provides an "identifiable benefit" in presently available form. *Juicy Whip*

*Inc. v. Orange Bang Inc.*, 185 F.3d 1364, 1366 (Fed. Cir. 1999). If the benefit exists, and there is a substantial likelihood the invention provides the benefit, it is useful. There can be no doubt, particularly in view of the Bedilion Declaration (at, *e.g.*, ¶¶ 10 and 15, Bedilion), that the present invention meets this test.

The threshold for determining whether an invention produces an identifiable benefit is low. *Juicy Whip*, 185 F.3d at 1366. Only those utilities that are so nebulous that a person of ordinary skill in the art would not know how to achieve an identifiable benefit and, at least according to the PTO guidelines, so-called “throwaway” utilities that are not directed to a person of ordinary skill in the art at all, do not meet the statutory requirement of utility. Utility Examination Guidelines, 66 Fed. Reg. 1092 (Jan. 5, 2001).

Knowledge of the biological function or role of a biological molecule has never been required to show real-world benefit. In its most recent explanation of its own utility guidelines, the PTO acknowledged so much (66 F.R. at 1095):

[T]he utility of a claimed DNA does not necessarily depend on the function of the encoded gene product. A claimed DNA may have specific and substantial utility because, *e.g.*, it hybridizes near a disease-associated gene or it has gene-regulating activity.

By implicitly requiring knowledge of biological function for any claimed nucleic acid, the Examiner has, contrary to law, elevated what is at most an evidentiary factor into an absolute requirement of utility. Rather than looking to the biological role or function of the claimed invention, the Examiner should have looked first to the benefits it is alleged to provide.

#### **B. Membership in a Class of Useful Products Can Be Proof of Utility**

Despite the uncontradicted evidence that the claimed polynucleotide encodes a polypeptide in the myosin family, the Examiner refused to impute the utility of the members of the myosin family to MHCH. In the Office Action, the Patent Examiner takes the position that, unless Appellants can identify which particular biological function within the class of myosins is possessed by MHCH, utility cannot be imputed. To demonstrate utility by membership in the class of myosins, the Examiner would require that all myosins possess a “common” utility.

There is no such requirement in the law. In order to demonstrate utility by membership in a class, the law requires only that the class not contain a substantial number of useless members.

So long as the class does not contain a substantial number of useless members, there is sufficient likelihood that the claimed invention will have utility, and a rejection under 35 U.S.C. § 101 is improper. That is true regardless of how the claimed invention ultimately is used and whether or not the members of the class possess one utility or many. *See Brenner v. Manson*, 383 U.S. 519, 532 (1966); *Application of Kirk*, 376 F.2d 936, 943 (CCPA 1967).

Membership in a “general” class is insufficient to demonstrate utility only if the class contains a sufficient number of useless members such that a person of ordinary skill in the art could not impute utility by a substantial likelihood. There would be, in that case, a substantial likelihood that the claimed invention is one of the useless members of the class. In the few cases in which class membership did not prove utility by substantial likelihood, the classes did in fact include predominately useless members. *E.g.*, *Brenner* (man-made steroids); *Kirk* (same); *Natta* (man-made polyethylene polymers).

The Examiner addresses MHCH as if the general class in which it is included is not the myosin family, but rather all polynucleotides or all polypeptides, including the vast majority of useless theoretical molecules not occurring in nature, and thus not pre-selected by nature to be useful. While these “general classes” may contain a substantial number of useless members, the myosin family does not. The myosin family is sufficiently specific to rule out any reasonable possibility that MHCH would not also be useful like the other members of the family.

Because the Examiner has not presented any evidence that the myosin class of proteins has any, let alone a substantial number, of useless members, the Examiner must conclude that there is a “substantial likelihood” that the MHCH encoded by the claimed polynucleotide is useful. It follows that the claimed polynucleotide also is useful.

It is undisputed that known members of the myosin family are motor proteins involved in muscle contraction, intracellular movement, phagocytosis, and cytokinesis. A person of ordinary skill in the art need not know any more about how the claimed invention functions to use it, and the Examiner presents no evidence to the contrary. The Examiner then goes on to assume that the only use for MHCH absent knowledge as to how the myosin actually works is further study of MHCH itself.

Not so. As demonstrated by Appellants, knowledge that MHCH is a myosin is more than sufficient to make it useful for the diagnosis and treatment of heart and skeletal muscle disorders,



developmental disorders, and cell proliferative disorders, including cancer. Indeed, MHCH has been shown to be expressed in hematopoietic/immune system, gastrointestinal, musculoskeletal, and reproductive tissues, and in tissues associated with cancer (Specification at page 18, lines 12-17). The Examiner must accept these facts to be true unless the Examiner can provide evidence or sound scientific reasoning to the contrary. But the Examiner has not done so.

**C. Because the uses of polynucleotides encoding MHCH in toxicology testing, drug discovery, and disease diagnosis are practical uses beyond mere study of the invention itself, the claimed invention has substantial utility.**

The PTO rejected the claims at issue on the ground that the use of an invention as a tool for research is not a “substantial” use. Because the PTO’s rejection assumes a substantial overstatement of the law, and is incorrect in fact, it must be overturned.

There is no authority for the proposition that use as a tool for research is not a substantial utility. Indeed, the Patent Office has recognized that just because an invention is used in a research setting does not mean that it lacks utility (MPEP § 2107):

Many research tools such as gas chromatographs, screening assays, and nucleotide sequencing techniques have a clear, specific and unquestionable utility (e.g., they are useful in analyzing compounds). An assessment that focuses on whether an invention is useful only in a research setting thus does not address whether the specific invention is in fact “useful” in a patent sense. Instead, Office personnel must distinguish between inventions that have a specifically identified utility and inventions whose specific utility requires further research to identify or reasonably confirm.

The Patent Office’s actual practice has been, at least until the present, consistent with that approach. It has routinely issued patents for inventions whose only use is to facilitate research, such as DNA ligases. These are acknowledged by the PTO’s Training Materials themselves to be useful, as well as DNA sequences used, for example, as markers.

Only a limited subset of research uses are not “substantial” utilities: those in which the only known use for the claimed invention is to be an **object** of further study, thus merely inviting further research. This follows from *Brenner*, in which the U.S. Supreme Court held that a process for making a compound does not confer a substantial benefit where the only known use of the compound was to be the object of further research to determine its use. *Id.* at 535. Similarly, in *Kirk*, the Court held that a compound would not confer substantial benefit on the public merely because it might be used to synthesize some other, unknown compound that would

confer substantial benefit. *Kirk*, 376 F.2d at 940, 945 (“What Appellants are really saying to those in the art is take these steroids, experiment, and find what use they do have as medicines.”). Nowhere do those cases state or imply, however, that a material cannot be patentable if it has some other beneficial use in research.

As used in toxicology testing, drug discovery, and disease diagnosis, the claimed invention has a beneficial use in research other than studying the claimed invention or its protein products. It is a tool, rather than an object, of research. The data generated in gene expression monitoring using the claimed invention as a tool is **not** used merely to study the claimed polynucleotide itself, but rather to study properties of tissues, cells, and potential drug candidates and toxins. Without the claimed invention, the information regarding the properties of tissues, cells, drug candidates and toxins is less complete. (Bedilion Declaration at ¶ 15.)

The claimed invention has numerous additional uses as a research tool, each of which alone is a “substantial utility.” These include uses such as diagnostic assays (e.g., pages 36-39), chromosomal markers (e.g., pages 39-40), and ligand screening assays (e.g., page 40).

**IV. By Requiring the Patent Appellant to Assert a Particular or Unique Utility, the Patent Examination Utility Guidelines and Training Materials Applied by the Patent Examiner Misstate the Law**

There is an additional, independent reason to overturn the rejections: to the extent the rejections are based on Revised Interim Utility Examination Guidelines (64 FR 71427, December 21, 1999), the final Utility Examination Guidelines (66 FR 1092, January 5, 2001) and/or the Revised Interim Utility Guidelines Training Materials (USPTO Website [www.uspto.gov](http://www.uspto.gov), March 1, 2000), the Guidelines and Training Materials are themselves inconsistent with the law.

The Training Materials, which direct the Examiners regarding how to apply the Utility Guidelines, address the issue of specificity with reference to two kinds of asserted utilities: “specific” utilities which meet the statutory requirements, and “general” utilities which do not. The Training Materials define a “specific utility” as follows:

A [specific utility] is *specific* to the subject matter claimed. This contrasts to *general* utility that would be applicable to the broad class of invention. For example, a claim to a polynucleotide whose use is disclosed simply as “gene probe” or “chromosome marker” would not be considered to be specific in the absence of a disclosure of a specific DNA

target. Similarly, a general statement of diagnostic utility, such as diagnosing an unspecified disease, would ordinarily be insufficient absent a disclosure of what condition can be diagnosed.

The Training Materials distinguish between “specific” and “general” utilities by assessing whether the asserted utility is sufficiently “particular,” *i.e.*, unique (Training Materials at p.52) as compared to the “broad class of invention.” (In this regard, the Training Materials appear to parallel the view set forth in Stephen G. Kunin, Written Description Guidelines and Utility Guidelines, 82 J.P.T.O.S. 77, 97 (Feb. 2000) (“With regard to the issue of specific utility the question to ask is whether or not a utility set forth in the specification is *particular* to the claimed invention.”)).

Such “unique” or “particular” utilities never have been required by the law. To meet the utility requirement, the invention need only be “practically useful,” *Natta*, 480 F.2d 1 at 1397, and confer a “specific benefit” on the public. *Brenner*, 383 U.S. at 534. Thus, incredible “throw-away” utilities, such as trying to “patent a transgenic mouse by saying it makes great snake food,” do not meet this standard. Karen Hall, Genomic Warfare, *The American Lawyer* 68 (June 2000) (quoting John Doll, Chief of the Biotech Section of USPTO).

This does not preclude, however, a general utility, contrary to the statement in the Training Materials where “specific utility” is defined (page 5). Practical real-world uses are not limited to uses that are unique to an invention. The law requires that the practical utility be “definite,” not particular.

*Montedison*, 664 F.2d at 375. Appellant is not aware of any court that has rejected an assertion of utility on the grounds that it is not “particular” or “unique” to the specific invention. Where courts have found utility to be too “general,” it has been in those cases in which the asserted utility in the patent disclosure was not a practical use that conferred a specific benefit. That is, a person of ordinary skill in the art would have been left to guess as to how to benefit at all from the invention. In *Kirk*, for example, the CCPA held the assertion that a man-made steroid had “useful biological activity” was insufficient where there was no information in the specification as to how that biological activity could be practically used. *Kirk*, 376 F.2d at 941.

The fact that an invention can have a particular use does not provide a basis for requiring a particular use. See *Brana*, *supra* (disclosure describing a claimed antitumor compound as being homologous to an antitumor compound having activity against a “particular” type of cancer

was determined to satisfy the specificity requirement). “Particularity” is not and never has been the *sine qua non* of utility; it is, at most, one of many factors to be considered.

As described *supra*, broad classes of inventions can satisfy the utility requirement so long as a person of ordinary skill in the art would understand how to achieve a practical benefit from knowledge of the class. Only classes that encompass a significant portion of nonuseful members would fail to meet the utility requirement. *Supra* § II.B.2 (*Montedison*, 664 F.2d at 374-75).

The Training Materials fail to distinguish between broad classes that convey information of practical utility and those that do not, lumping all of them into the latter, unpatentable category of “general” utilities. As a result, the Training Materials paint with too broad a brush. Rigorously applied, they would render unpatentable whole categories of inventions that heretofore have been considered to be patentable and that have indisputably benefitted the public, including the claimed invention. *See supra* § II.B. Thus the Training Materials cannot be applied consistently with the law.

**Issue 2 – Whether claims 23-31 meet the enablement requirement of 35 U.S.C. § 112, first paragraph**

**To the extent the rejection of the claimed invention under 35 U.S.C. § 112, first paragraph, is based on the improper rejection for lack of utility under 35 U.S.C. § 101, it must be reversed.**

The rejection set forth in the Office Action is based on the assertions discussed above, i.e., that the claimed invention lacks patentable utility. To the extent that the rejection under § 112, first paragraph, is based on the improper allegation of lack of patentable utility under § 101, it fails for the same reasons.

**Issue 3– Whether one of ordinary skill in the art would know how to make the claimed polynucleotide variants and fragments according to claims 23, 26-28, and 30, so as to satisfy the enablement requirement of 35 U.S.C. §112, first paragraph**

**The rejection of claims 23, 26, 27, 28, and 30 is improper because the claimed variants and fragments of SEQ ID NO:1 are amply enabled by the disclosure of the specification.**

In particular, the Examiner alleges that “searching for the specific nucleotides to change (deletion, insertion, substitution, or combinations thereof) in a polynucleotide to make any polynucleotide of any nucleotide sequence having 70% identity to any polynucleotide encoding SEQ ID NO:1 or any fragment thereof or any polynucleotide having 70% identity to SEQ ID NO:2 or any fragment thereof is well outside the realm of routine experimentation and predictability in the art...” (Office Action of April 4, 2003, page 5).

As set forth in *In re Marzocchi*, 169 USPQ 367, 369 (CCPA 1971):

The first paragraph of § 112 requires nothing more than objective enablement. How such a teaching is set forth, either by the use of illustrative examples or by broad terminology, is of no importance.

As a matter of Patent Office practice, then, a specification disclosure which contains a teaching of the manner and process of making and using the invention in terms which correspond in scope to those used in describing and defining the subject matter sought to be patented *must* be taken as in compliance with the enabling requirement of the first paragraph of § 112 *unless* there is reason to doubt the objective truth of the statements contained therein which must be relied on for enabling support.

Appellants respectfully point out that the claims of the instant application are drawn to **naturally-occurring** variants. Thus it is not necessary to screen every conceivable variant which might be made using recombinant methods, as all that is claimed are those variant sequences which are found in nature. Given the sequences of SEQ ID NO:1 and SEQ ID NO:2, one of ordinary skill in the art could readily identify a polynucleotide encoding a polypeptide comprising a naturally occurring amino acid sequence at least 90% identical to an amino acid sequence of SEQ ID NO:1 or a polynucleotide comprising a naturally occurring polynucleotide

sequence at least 70% identical to a polynucleotide sequence of SEQ ID NO:2, using well known methods of sequence analysis without any undue experimentation. For example, the identification of relevant polynucleotides could be performed by hybridization and/or PCR techniques that were well-known to those skilled in the art at the time the subject application was filed and/or described throughout the Specification of the instant application. See, e.g., page 12, line 13 through page 13, line 9; page 25, lines 2-6 and 18-28; and Example VI at pages 45-46. Thus, one skilled in the art need not make and test vast numbers of polynucleotides. Instead, one skilled in the art need only screen a cDNA library or use appropriate PCR conditions to identify relevant polynucleotides that already exist in nature. The skilled artisan would also know how to use the claimed polynucleotides, for example in expression profiling, disease diagnosis, or detection of related sequences as discussed above.

The specification also describes the expression vectors into which the claimed fragments could be inserted, and the construction of fusion proteins (pages 22-24 and page 47, line 8 through page 48, line 3). The specification describes, for example, specific assays for myosin activity on page 48; binding assays to detect molecular interactions of "MHCH or biologically active fragments thereof" on page 50, lines 4-19; and immunological methods for detecting and measuring MHCH on page 25, lines 7-16. These methods could be used to detect and characterize peptide variants and fragments of SEQ ID NO:1. Given this guidance, one of ordinary skill in the art would readily understand how to select and screen polynucleotides encoding fragments of SEQ ID NO:1 with ATPase activity or immunogenic activity without any undue experimentation.

Furthermore, the claims are directed to polynucleotides, not polypeptides, and it is the functionality of the claimed polynucleotides, not the polypeptides encoded by them, that is relevant. Members of the claimed genus of variants may include, for example, mutant alleles associated with diseases, or single nucleotide polymorphisms (SNPs). Members of the claimed genus of variants may be useful even if they encode defective MHCH polypeptides. For example, the variant polynucleotides could be used for the detection of sequences related to MHCH (see the specification at page 25, lines 17-28, and page 36, lines 24-30) including MHCH variants that may be associated with disease states, such as the diseases listed on page 27, line 16

through page 28, line 3, of the specification. See the specification at, for example, pages 36-40 for disclosure of how to use the claimed sequences in diagnostic assays.

The Examiner has cited Attwood et al., identifying some of the difficulties that may be involved in predicting protein function; however, this reference does not suggest that functional homology cannot be inferred by a reasonable probability in this case. At most, this article suggests that it is difficult to make predictions about function with certainty. The standard applicable in this case is not proof to certainty, but rather, proof to a reasonable probability. In fact, Attwood et al. point out the value of sequence analysis, in particular with regard to the identification of conserved motifs in proteins. “Because motifs usually reflect some vital structural or functional role (Fig. 2), they **effectively** provide diagnostic family signatures” (Emphasis added; Attwood et al. p. 332, col. 2).

The Examiner alleges that “the specification does not teach the specific structural/catalytic amino acids and the structural motifs essential for protein activity/function which cannot be altered. Such experimentation entails selecting specific nucleotides to change (deletion, insertion, substitution, or combinations thereof) in a polynucleotide to make the claimed polynucleotide and determining by assays whether the polypeptide has activity” (Final Office Action, page 4). This is untrue. Again, Appellants respectfully point out that the claims of the instant application are drawn to **naturally-occurring** variants. Through the process of natural selection, nature will have determined the appropriate sequences.

Appellants also point out that the specification does teach “specific structural motifs essential for protein activity/function.” The specification describes similarities between SEQ ID NO:1 and *C. elegans* myosin (g1279777) and *H. annuus* unconventional myosin (g2444174), including the presence of the myosin head domain, myosin heavy chain, and light chain binding site signatures (see specification, for example, at page 17, line 26 through page 18, line 9 and Figure 2). The myosin head domain is known to possess ATPase activity and contain actin binding sites. At the time of filing of the instant application, the crystallographic structure of a myosin motor head was available to assist one of skill in the art in the determination of “specific catalytic residues and structural motifs,” particularly those critical for ATPase activity and actin binding (See reference of Rayment et al. (1993) Science 261:50-58, previously submitted with the response to the Office Action of April 4, 2003).

Further, the Examiner requires working examples (Office Action, page 4). There is no such requirement under the law to provide “working examples.” As set forth in *In re Borkowski*, 164 USPQ 642, 645 (CCPA 1970) (footnote omitted):

However, as we have stated in a number of opinions, a specification need not contain a working example if the invention is otherwise disclosed in such a manner that one skilled in the art will be able to practice it without an undue amount of experimentation.

See also M.P.E.P. 2164.02 as follows:

Compliance with the enablement requirement of 35 U.S.C. 112, first paragraph, does not turn on whether an example is disclosed. An example may be “working” or “prophetic”... A prophetic example describes an embodiment of the invention based on predicted results rather than work actually conducted or results actually achieved.

Thus, there is no requirement under the law to provide “working examples” of what is claimed. Rather, one looks to whether the specification provides a description of how to make what is claimed. The present specification provides the requisite description.

Contrary to the standard set forth in *Marzocchi* and *Borkowski*, the Examiner has failed to provide any *reasons* why one would doubt that the guidance provided by the present specification would enable one to make and use the recited polynucleotides. Hence, a *prima facie* case for non-enablement has not been established. For at least the above reasons, withdrawal of the enablement rejections under 35 U.S.C. § 112, first paragraph, is respectfully requested.

**Issue 4– Whether claims 23, 26-28, 30, and 31 meet the written description requirement of 35 U.S.C. §112, first paragraph**

**The rejection of claims 23, 26-28, and 31 is improper because the Specification provides an adequate written description of the claimed variants and fragments of SEQ ID NO:2.**



The requirements necessary to fulfill the written description requirement of 35 U.S.C. 112, first paragraph, are well established by case law.

. . . the applicant must also convey with reasonable clarity to those skilled in the art that, as of the filing date sought, he or she was in possession *of the invention*. The invention is, for purposes of the "written description" inquiry, *whatever is now claimed*. *Vas-Cath, Inc. v. Mahurkar*, 19 USPQ2d 1111, 1117 (Fed. Cir. 1991)

Attention is also drawn to the Patent and Trademark Office's own "Guidelines for Examination of Patent Applications Under the 35 U.S.C. Sec. 112, para. 1", published January 5, 2001, which provide that :

An applicant may also show that an invention is complete by disclosure of sufficiently detailed, relevant identifying characteristics<sup>42</sup> which provide evidence that applicant was in possession of the claimed invention,<sup>43</sup> i.e., complete or partial structure, other physical and/or chemical properties, functional characteristics when coupled with a known or disclosed correlation between function and structure, or some combination of such characteristics.<sup>44</sup> What is conventional or well known to one of ordinary skill in the art need not be disclosed in detail.<sup>45</sup> If a skilled artisan would have understood the inventor to be in possession of the claimed invention at the time of filing, even if every nuance of the claims is not explicitly described in the specification, then the adequate description requirement is met.<sup>46</sup>

Thus, the written description standard is fulfilled by both what is specifically disclosed and what is conventional or well known to one skilled in the art.

SEQ ID NO:1 and SEQ ID NO:2 are specifically disclosed in the application (see, for example, page 17, lines 19-34). Variants of SEQ ID NO:1 and SEQ ID NO:2 are described, for example, at page 18, lines 18-33. Incyte clones in which the nucleic acids encoding the human myosin heavy chain homolog were first identified and libraries from which those clones were isolated are described, for example, at page 17, lines 19-25 of the Specification. Chemical and structural features of SEQ ID NO:1 are described, for example, on page 17, line 26 through page 18, line 9. Given SEQ ID NO:1, one of ordinary skill in the art would recognize naturally-occurring variants of SEQ ID NO:1 having 90% sequence identity to SEQ ID NO:1. Given SEQ ID NO:2, one of ordinary skill in the art would recognize naturally-occurring variants of SEQ ID NO:2 having 70% sequence identity to SEQ ID NO:2. Accordingly, the Specification provides an adequate written description of the recited polypeptide sequences.

The Office Action has further asserted that the claims are not supported by an adequate written description because the specification "only provides the following representative species encompassed by these claims: a polynucleotide consisting of the nucleotide sequence of SEQ ID NO:2 and a polynucleotide encoding a polypeptide consisting of the amino acid sequence of SEQ ID NO:1.... Given this lack of additional representative species as encompassed by the claims, Applicants have failed to sufficiently describe the claimed invention"...

Such a position is believed to present a misapplication of the law.

**1. The present claims specifically define the claimed genus through the recitation of chemical structure**

Court cases in which "DNA claims" have been at issue commonly emphasize that the recitation of structural features or chemical or physical properties are important factors to consider in a written description analysis of such claims. For example, in *Fiers v. Revel*, 25 USPQ2d 1601, 1606 (Fed. Cir. 1993), the court stated that:

If a conception of a DNA requires a precise definition, such as by structure, formula, chemical name or physical properties, as we have held, then a description also requires that degree of specificity.

In a number of instances in which claims to DNA have been found invalid, the courts have noted that the claims attempted to define the claimed DNA in terms of functional characteristics without any reference to structural features. As set forth by the court in *University of California v. Eli Lilly and Co.*, 43 USPQ2d 1398, 1406 (Fed. Cir. 1997):

In claims to genetic material, however, a generic statement such as "vertebrate insulin cDNA" or "mammalian insulin cDNA," without more, is not an adequate written description of the genus because it does not distinguish the claimed genus from others, except by function.

Thus, the mere recitation of functional characteristics of a DNA, without the definition of structural features, has been a common basis by which courts have found invalid claims to DNA. For example, in *Lilly*, 43 USPQ2d at 1407, the court found invalid for violation of the written description requirement the following claim of U.S. Patent No. 4,652,525:

1. A recombinant plasmid replicable in procaryotic host containing within its nucleotide sequence a subsequence having the structure of the reverse transcript of an mRNA of a vertebrate, which mRNA encodes insulin.

In *Fiers*, 25 USPQ2d at 1603, the parties were in an interference involving the following count:

A DNA which consists essentially of a DNA which codes for a human fibroblast interferon-beta polypeptide.

Party Revel in the *Fiers* case argued that its foreign priority application contained an adequate written description of the DNA of the count because that application mentioned a potential method for isolating the DNA. The Revel priority application, however, did not have a description of any particular DNA structure corresponding to the DNA of the count. The court therefore found that the Revel priority application lacked an adequate written description of the subject matter of the count.

Thus, in *Lilly* and *Fiers*, nucleic acids were defined on the basis of functional characteristics and were found not to comply with the written description requirement of 35 U.S.C. §112; *i.e.*, "an mRNA of a vertebrate, which mRNA encodes insulin" in *Lilly*, and "DNA which codes for a human fibroblast interferon-beta polypeptide" in *Fiers*. In contrast to the situation in *Lilly* and *Fiers*, the claims at issue in the present application define polynucleotides in terms of chemical structure, rather than on functional characteristics. For example, the "variant language" of independent claim 30 recites chemical structure to define the claimed genus:

An isolated polynucleotide selected from the group consisting of:...

- b) a polynucleotide comprising a naturally occurring polynucleotide sequence at least 70% identical to a polynucleotide sequence of SEQ ID NO:2...

From the above it should be apparent that the claims of the subject application are fundamentally different from those found invalid in *Lilly* and *Fiers*. The subject matter of the present claims is defined in terms of the chemical structure of SEQ ID NO:2. In the present case, there is no reliance merely on a description of functional characteristics of the polynucleotides recited by the claims. In fact, there is no recitation of functional characteristics. Moreover, if such functional recitations were included, it would add to the structural characterization of the recited polynucleotides. The polynucleotides defined in the claims of the present application recite structural features, and cases such as *Lilly* and *Fiers* stress that the recitation of structure is an important factor to consider in a written description analysis of claims of this type. By failing

to base its written description inquiry "on whatever is now claimed," the Office Action failed to provide an appropriate analysis of the present claims and how they differ from those found not to satisfy the written description requirement in *Lilly and Fiers*

**2. The present claims do not define a genus which is "highly variant"**

Furthermore, the claims at issue do not describe a genus which could be characterized as "highly variant." Available evidence illustrates that the claimed genus is of narrow scope.

In support of this assertion, the Examiner's attention is directed to the enclosed reference by Brenner et al. ("Assessing sequence comparison methods with reliable structurally identified distant evolutionary relationships," Proc. Natl. Acad. Sci. USA (1998) 95:6073-6078). Through exhaustive analysis of a data set of proteins with known structural and functional relationships and with <90% overall sequence identity, Brenner et al. have determined that 30% identity is a reliable threshold for establishing evolutionary homology between two sequences aligned over at least 150 residues. (Brenner et al., pages 6073 and 6076.) Furthermore, local identity is particularly important in this case for assessing the significance of the alignments, as Brenner et al. further report that  $\geq 40\%$  identity over at least 70 residues is reliable in signifying homology between proteins. (Brenner et al., page 6076.)

The present application is directed, *inter alia*, to myosin proteins related to the amino acid sequence of SEQ ID NO:1. In accordance with Brenner et al, naturally occurring molecules may exist which could be characterized as myosin proteins and which have as little as 40% identity over at least 70 residues to SEQ ID NO:1. The "variant language" of the present claims recites, for example, a polynucleotide encoding "a polypeptide comprising a naturally occurring amino acid sequence at least 90% identical to an amino acid sequence of SEQ ID NO:1" and "a polynucleotide comprising a naturally occurring polynucleotide sequence at least 70% identical to a polynucleotide sequence of SEQ ID NO:2" (note that SEQ ID NO:1 has 612 amino acid residues). This variation is far less than that of all potential myosin proteins related to SEQ ID NO:1, i.e., those myosin proteins having as little as 40% identity over at least 70 residues to SEQ ID NO:1.

**3. The state of the art at the time of the present invention is further advanced than at the time of the *Lilly* and *Fiers* applications**

In the *Lilly* case, claims of U.S. Patent No. 4,652,525 were found invalid for failing to comply with the written description requirement of 35 U.S.C. §112. The '525 patent claimed the benefit of priority of two applications, Application Serial No. 801,343 filed May 27, 1977, and Application Serial No. 805,023 filed June 9, 1977. In the *Fiers* case, party Revel claimed the benefit of priority of an Israeli application filed on November 21, 1979. Thus, the written description inquiry in those case was based on the state of the art at essentially at the "dark ages" of recombinant DNA technology.

The present application has a priority date of November 5, 1998. Much has happened in the development of recombinant DNA technology in the 19 or more years from the time of filing of the applications involved in *Lilly* and *Fiers* and the present application. For example, the technique of polymerase chain reaction (PCR) was invented. Highly efficient cloning and DNA sequencing technology has been developed. Large databases of protein and nucleotide sequences have been compiled. Much of the raw material of the human and other genomes has been sequenced. With these remarkable advances one of skill in the art would recognize that, given the sequence information of SEQ ID NO:1 and SEQ ID NO:2, and the additional extensive detail provided by the subject application, the present inventors were in possession of the claimed polynucleotide variants at the time of filing of this application.

CONCLUSIONS

Appellants respectfully submit that rejections for lack of utility based, *inter alia*, on an allegation of "lack of specificity," as set forth in the Office Action and as justified in the Revised Interim and final Utility Guidelines and Training Materials, are not supported in the law. Neither are they scientifically correct, nor supported by any evidence or sound scientific reasoning. These rejections are alleged to be founded on facts in court cases such as *Brenner* and *Kirk*, yet those facts are clearly distinguishable from the facts of the instant application, and indeed most if not all nucleotide and protein sequence applications. Nevertheless, the PTO is attempting to

mold the facts and holdings of these prior cases, “like a nose of wax,”<sup>2</sup> to target rejections of claims to polypeptide and polynucleotide sequences, as well as to claims to methods of detecting said polynucleotide sequences, where biological activity information has not been proven by laboratory experimentation, and they have done so by ignoring perfectly acceptable utilities fully disclosed in the specifications as well as well-established utilities known to those of skill in the art. As is disclosed in the specification, and even more clearly, as one of ordinary skill in the art would understand, the claimed invention has well-established, specific, substantial and credible utilities. The rejections are, therefore, improper and should be reversed.

Moreover, to the extent the above rejections were based on the Revised Interim and final Examination Guidelines and Training Materials, those portions of the Guidelines and Training Materials that form the basis for the rejections should be determined to be inconsistent with the law.

The written description rejections under 35 U.S.C. § 112, first paragraph, should be reversed based on at least the arguments presented above. The Examiner failed to base the written description inquiry “on whatever is now claimed.” Consequently, the Examiner did not provide an appropriate analysis of the present claims and how they differ from those found not to satisfy the written description requirement in cases such as *Lilly* and *Fiers*. In particular, the claims of the subject application are fundamentally different from those found invalid in *Lilly* and *Fiers*. The subject matter of the present claims is defined in terms of the chemical structure of SEQ ID NO:1 and SEQ ID NO:2. The courts have stressed that structural features are important factors to consider in a written description analysis of claims to nucleic acids and proteins. In addition, the genus of polypeptides defined by the present claims is adequately described, as evidenced by Brenner et al. Furthermore, there have been remarkable advances in the state of the art since the *Lilly* and *Fiers* cases, and these advances were given no consideration whatsoever in the position set forth by the Examiner.

Due to the urgency of this matter, including its economic and public health implications, an expedited review of this appeal is earnestly solicited.

---

<sup>2</sup>“The concept of patentable subject matter under §101 is not ‘like a nose of wax which may be turned and twisted in any direction \* \* \*.’ *White v. Dunbar*, 119 U.S. 47, 51.” (*Parker v. Flook*, 198 USPQ 193 (US SupCt 1978))

If the USPTO determines that any additional fees are due, the Commissioner is hereby authorized to charge Deposit Account No. **09-0108**.

**This brief is enclosed in triplicate**

Date:

5 March 2004

Respectfully submitted,

INCYTE CORPORATION



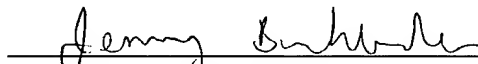
James M. Verna, Ph.D.

Reg. No. 33,287

Direct Dial Telephone: (650) 845 -5415

Date:

March 5, 2004



Jenny Buchbinder, Ph.D.

Reg. No. 48,588

Direct Dial Telephone: (650) 843-7212

**Customer No.: 27904**

3160 Porter Drive

Palo Alto, California 94304

Phone: (650) 855-0555

Fax: (650) 849-8886

**Enclosures:**

1. Rockett et al., Differential gene expression in drug metabolism and toxicology: practicalities, problems and potential, 29 Xenobiotica No. 7, 655 (1999)
2. Lashkari et al., Whole genome analysis: Experimental access to all genome sequenced segments through larger-scale efficient oligonucleotide synthesis and PCR, 94 Proc. Nat. Acad. Sci. 8945 (Aug. 1997).
3. Emile F. Nuwaysir et al., Microarrays and Toxicology: The Advent of Toxicogenomics, 24 Molecular Carcinogenesis 153 (1999);
4. Sandra Steiner and N. Leigh Anderson, Expression profiling in toxicology -- potentials and limitations, 112-13 Toxicology Letters 467 (2000).
5. John C. Rockett and David J. Dix, Application of DNA Arrays to Toxicology, 107 Environ. Health Perspec. 681, No. 8 (1999).
6. Email from the primary investigator on the Nuwaysir paper, Dr. Cynthia Afshari, to an Incyte employee, dated July 3, 2000, as well as the original message to which she was responding.
7. Brenner et al., Proc. Natl. Acad. Sci. 95:6073-78 (1998).
8. Rayment et al. Science 261:50-58 (1993).

**APPENDIX - CLAIMS ON APPEAL**

23. An isolated polynucleotide encoding a polypeptide selected from the group consisting of:

- a) a polypeptide comprising an amino acid sequence of SEQ ID NO:1,
- b) a polypeptide comprising a naturally occurring amino acid sequence at least 90% identical to an amino acid sequence of SEQ ID NO:1, said polypeptide having ATPase activity,
- c) a biologically active fragment of a polypeptide having an amino acid sequence of SEQ ID NO:1, said fragment having ATPase activity, and
- d) an immunogenic fragment of a polypeptide consisting of an amino acid sequence of SEQ ID NO:1, wherein said fragment comprises at least 15 contiguous amino acid residues of SEQ ID NO:1.

24. An isolated polynucleotide of claim 23 comprising a polynucleotide encoding a polypeptide comprising an amino acid sequence of SEQ ID NO:1.

25. An isolated polynucleotide of claim 24 comprising a polynucleotide sequence of SEQ ID NO:2.

26. A recombinant polynucleotide comprising a promoter sequence operably linked to a polynucleotide of claim 23.

27. A cell transformed with a recombinant polynucleotide of claim 26.

28. A method of producing a polypeptide, the method comprising:

- a) culturing a cell under conditions suitable for expression of the polypeptide, wherein said cell is transformed with a recombinant polynucleotide, and said recombinant polynucleotide comprises a promoter sequence operably linked to a polynucleotide of claim 23, and



- b) recovering the polypeptide so expressed.

29. A method of claim 28, wherein the polypeptide comprises an amino acid sequence of SEQ ID NO:1.

30. An isolated polynucleotide selected from the group consisting of:

- a) a polynucleotide comprising a polynucleotide sequence of SEQ ID NO:2,
- b) a polynucleotide comprising a naturally occurring polynucleotide sequence at least 70% identical to a polynucleotide sequence of SEQ ID NO:2,
- c) a polynucleotide complementary to a polynucleotide of a),
- d) a polynucleotide complementary to a polynucleotide of b), and
- e) an RNA equivalent of a)-d).

31. An isolated polynucleotide consisting of at least 25 contiguous nucleotides of a polynucleotide selected from the group consisting of:

- a) a polynucleotide consisting of a polynucleotide sequence of SEQ ID NO:2, and
- b) a polynucleotide complementary to a polynucleotide of a).

## Differential gene expression in drug metabolism and toxicology: practicalities, problems and potential

JOHN C. ROCKETT†, DAVID J. ESDAILE‡  
and G. GORDON GIBSON\*

Molecular Toxicology Laboratory, School of Biological Sciences, University of Surrey,  
Guildford, Surrey, GU2 5XH, UK

Received January 8, 1999

1. An important feature of the work of many molecular biologists is identifying which genes are switched on and off in a cell under different environmental conditions or subsequent to xenobiotic challenge. Such information has many uses, including the deciphering of molecular pathways and facilitating the development of new experimental and diagnostic procedures. However, the student of gene hunting should be forgiven for perhaps becoming confused by the mountain of information available as there appears to be almost as many methods of discovering differentially expressed genes as there are research groups using the technique.

2. The aim of this review was to clarify the main methods of differential gene expression analysis and the mechanistic principles underlying them. Also included is a discussion on some of the practical aspects of using this technique. Emphasis is placed on the so-called 'open' systems, which require no prior knowledge of the genes contained within the study model. Whilst these will eventually be replaced by 'closed' systems in the study of human, mouse and other commonly studied laboratory animals, they will remain a powerful tool for those examining less fashionable models.

3. The use of suppression-PCR subtractive hybridization is exemplified in the identification of up- and down-regulated genes in rat liver following exposure to phenobarbital, a well-known inducer of the drug metabolizing enzymes.

4. Differential gene display provides a coherent platform for building libraries and microchip arrays of 'gene fingerprints' characteristic of known enzyme inducers and xenobiotic toxicants, which may be interrogated subsequently for the identification and characterization of xenobiotics of unknown biological properties.

### Introduction

It is now apparent that the development of almost all cancers and many non-neoplastic diseases are accompanied by altered gene expression in the affected cells compared to their normal state (Hunter 1991, Wynford-Thomas 1991, Vogelstein and Kinzler 1993, Semenza 1994, Cassidy 1995, Kleinjan and Van Hegningen 1998). Such changes also occur in response to external stimuli such as pathogenic micro-organisms (Rohn *et al.* 1996, Singh *et al.* 1997, Griffin and Krishna 1998, Lunney 1998) and xenobiotics (Sewall *et al.* 1995, Dogra *et al.* 1998, Ramana and Kohli 1998), as well as during the development of undifferentiated cells (Hecht 1998, Rudin and Thompson 1998, Schneider-Maunoury *et al.* 1998). The potential medical and therapeutic benefits of understanding the molecular changes which occur in any given cell in progressing from the normal to the 'altered' state are enormous. Such profiling essentially provides a 'fingerprint' of each step of a

\* Author for correspondence; e-mail: g.gibson@surrey.ac.uk

† Current Address: US Environmental Protection Agency, National Health and Environmental Effects, Research Laboratory, Reproductive Toxicology Division, Research Triangle Park, NC 27711, USA.

‡ Rhone-Poulenc Agrochemicals, Toxicology Department, Sophia-Antipolis, Nice, France.

cell's development or response and should help in the elucidation of specific and sensitive biomarkers representing, for example, different types of cancer or previous exposure to certain classes of chemicals that are enzyme inducers.

In drug metabolism, many of the xenobiotic-metabolizing enzymes (including the well-characterized isoforms of cytochrome P450) are inducible by drugs and chemicals in man (Pelkonen *et al.* 1998), predominantly involving transcriptional activation of not only the cognate cytochrome P450 genes, but additional cellular proteins which may be crucial to the phenomenon of induction. Accordingly, the development of methodology to identify and assess the full complement of genes that are either up- or down-regulated by inducers are crucial in the development of knowledge to understand the precise molecular mechanisms of enzyme induction and how this relates to drug action. Similarly, in the field of chemical-induced toxicity, it is now becoming increasingly obvious that most adverse reactions to drugs and chemicals are the result of multiple gene regulation, some of which are causal and some of which are casually-related to the toxicological phenomenon *per se*. This observation has led to an upsurge in interest in gene-profiling technologies which differentiate between the control and toxin-treated gene pools in target tissues and is, therefore, of value in rationalizing the molecular mechanisms of xenobiotic-induced toxicity. Knowledge of toxin-dependent gene regulation in target tissues is not solely an academic pursuit as much interest has been generated in the pharmaceutical industry to harness this technology in the early identification of toxic drug candidates, thereby shortening the developmental process and contributing substantially to the safety assessment of new drugs. For example, if the gene profile in response to say a testicular toxin that has been well-characterized *in vivo* could be determined in the testis, then this profile would be representative of all new drug candidates which act via this specific molecular mechanism of toxicity, thereby providing a useful and coherent approach to the early detection of such toxicants. Whereas it would be informative to know the identity and functionality of all genes up/down regulated by such toxicants, this would appear a longer term goal, as the majority of human genes have not yet been sequenced, far less their functionality determined. However, the current use of gene profiling yields a *pattern* of gene changes for a xenobiotic of unknown toxicity which may be matched to that of well-characterized toxins, thus alerting the toxicologist to possible *in vivo* similarities between the unknown and the standard, thereby providing a platform for more extensive toxicological examination. Such approaches are beginning to gain momentum, in that several biotechnology companies are commercially producing 'gene chips' or 'gene arrays' that may be interrogated for toxicity assessment of xenobiotics. These chips consist of hundreds/thousands of genes, some of which are degenerate in the sense that not all of the genes are mechanistically-related to any one toxicological phenomenon. Whereas these chips are useful in broad-spectrum screening, they are maturing at a substantial rate, in that gene arrays are now becoming more specific, e.g. chips for the identification of changes in growth factor families that contribute to the aetiology and development of chemically-induced neoplasias.

Although documenting and explaining these genetic changes presents a formidable obstacle to understanding the different mechanisms of development and disease progression, the technology is now available to begin attempting this difficult challenge. Indeed, several 'differential expression analysis' methods have been developed which facilitate the identification of gene products that demonstrate

altered expression in cells of one population compared to another. These methods have been used to identify differential gene expression in many situations, including invading pathogenic microbes (Zhao *et al.* 1998), in cells responding to extracellular and intracellular microbial invasion (Duguid and Dinanuer 1990, Ragno *et al.* 1997, Maldarelli *et al.* 1998), in chemically treated cells (Syed *et al.* 1997, Rockett *et al.* 1999), neoplastic cells (Liang *et al.* 1992, Chang and Terzaghi-Howe 1998), activated cells (Gurskaya *et al.* 1996, Wan *et al.* 1996), differentiated cells (Hara *et al.* 1991, Guimaraes *et al.* 1995a, b), and different cell types (Davis *et al.* 1984, Hedrick *et al.* 1984, Xhu *et al.* 1998). Although differential expression analysis technologies are applicable to a broad range of models, perhaps their most important advantage is that, in most cases, absolutely no prior knowledge of the specific genes which are up- or down-regulated is required.

The field of differential expression analysis is a large and complex one, with many techniques available to the potential user. These can be categorized into several methodological approaches, including:

- (1) Differential screening,
- (2) Subtractive hybridization (SH) (includes methods such as chemical cross-linking subtraction—CCLS, suppression-PCR subtractive hybridization—SSH, and representational difference analysis—RDA),
- (3) Differential display (DD),
- (4) Restriction endonuclease facilitated analysis (including serial analysis of gene expression—SAGE—and gene expression fingerprinting—GEF),
- (5) Gene expression arrays, and
- (6) Expressed sequence tag (EST) analysis.

The above approaches have been used successfully to isolate differentially expressed genes in different model systems. However, each method has its own subtle (and sometimes not so subtle) characteristics which incur various advantages and disadvantages. Accordingly, it is the purpose of this review to clarify the mechanistic principles underlying the main differential expression methods and to highlight some of the broader considerations and implications of this very powerful and increasingly popular technique. Specifically, we will concentrate on the so-called 'open' systems, namely those which do not require any knowledge of gene sequences and, therefore, are useful for isolating unknown genes. Two 'closed' systems (those utilising previously identified gene sequences), EST analysis and the use of DNA arrays, will also be considered briefly for completeness. Whilst emphasis will often be placed on suppression PCR subtractive hybridization (SSH, the approach employed in this laboratory), it is the aim of the authors to highlight, wherever possible, those areas of common interest to those who use, or intend to use, differential gene expression analysis.

### Differential cDNA library screening (DS)

Despite the development of multiple technological advances which have recently brought the field of gene expression profiling to the forefront of molecular analysis, recognition of the importance of differential gene expression and characterization of differentially expressed genes has existed for many years. One of the original approaches used to identify such genes was described 20 years ago by St John and Davis (1979). These authors developed a method, termed 'differential plaque filter

hybridization', which was used to isolate galactose-inducible DNA sequences from yeast. The theory is simple: a genomic DNA library is prepared from normal, unstimulated cells of the test organism/tissue and multiple filter replicas are prepared. These replica blots are probed with radioactively (or otherwise) labelled complex cDNA probes prepared from the control and test cell mRNA populations. Those mRNAs which are differentially expressed in the treated cell population will show a positive signal only on the filter probed with cDNA from the treated cells. Furthermore, labelled cDNA from different test conditions can be used to probe multiple blots, thereby enabling the identification of mRNAs which are only up-regulated under certain conditions. For example, St John and Davis (1979) screened replica filters with acetate-, glucose- and galactose-derived probes in order to obtain genes induced specifically by galactose metabolism. Although groundbreaking in its time this method is now considered insensitive and time-consuming, as up to 2 months are required to complete the identification of genes which are differentially expressed in the test population. In addition, there is no convenient way to check that the procedure has worked until the whole process has been completed.

### **Subtractive Hybridization (SH)**

The developing concept of differential gene expression and the success of early approaches such as that described by St John and Davis (1979) soon gave rise to a search for more convenient methods of analysis. One of the first to be developed was SH, numerous variations of which have since been reported (see below). In general, this approach involves hybridization of mRNA/cDNA from one population (tester) to excess mRNA/cDNA from another (driver), followed by separation of the unhybridized tester fraction (differentially expressed) from the hybridized common sequences. This step has been achieved physically, chemically and through the use of selective polymerase chain reaction (PCR) techniques.

#### *Physical separation*

Original subtractive hybridization technology involved the physical separation of hybridized common species from unique single stranded species. Several methods of achieving this have been described, including hydroxyapatite chromatography (Sargent and Dawid 1983), avidin-biotin technology (Duguid and Dinauer 1990) and oligodT-latex separation (Hara *et al.* 1991). In the first approach, common mRNA species are removed by cDNA (from test cells)-mRNA (from control cells) subtractive hybridization followed by hydroxyapatite chromatography, as hydroxyapatite specifically adsorbs the cDNA-mRNA hybrids. The unabsorbed cDNA is then used either for the construction of a cDNA library of differentially expressed genes (Sargent and Dawid 1983, Schneider *et al.* 1988) or directly as a probe to screen a preselected library (Zimmerman *et al.* 1980, Davis *et al.* 1984, Hedrick *et al.* 1984). A schematic diagram of the procedure is shown in figure 1:

Less rigorous physical separation procedures coupled with sensitivity enhancing PCR steps were later developed as a means to overcome some of the problems encountered with the hydroxyapatite procedure. For example, Duguid and Dinauer (1990) described a method of subtraction utilizing biotin-affinity systems as a means to remove hybridized common sequences. In this process, both the control and tester mRNA populations are first converted to cDNA and an adaptor ('oligovector',

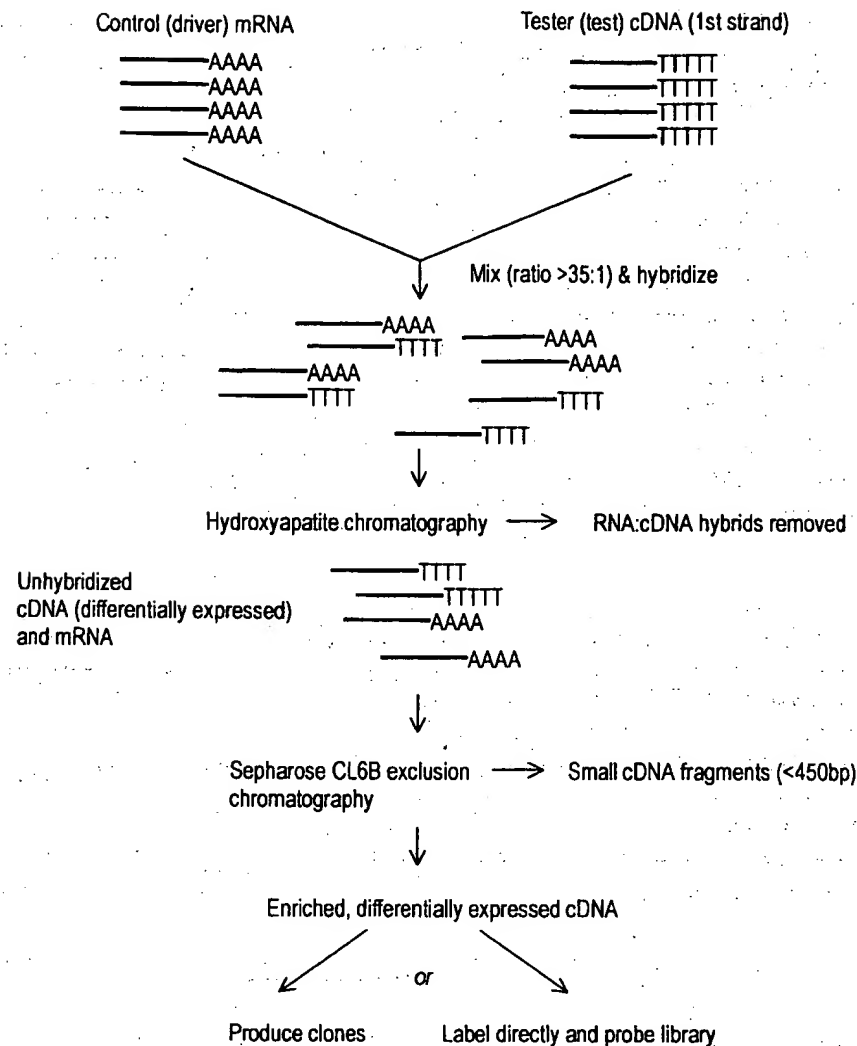


Figure 1. The hydroxyapatite method of subtractive hybridization. cDNA derived from the treated/alterd (tester) population is mixed with a large excess of mRNA from the control (driver) population. Following hybridization, mRNA-cDNA hybrids are removed by hydroxyapatite chromatography. The only cDNAs which remain are those which are differentially expressed in the treated/alterd population. In order to facilitate the recovery of full length clones, small cDNA fragments are removed by exclusion chromatography. The remaining cDNAs are then cloned into a vector for sequencing, or labelled and used directly to probe a library, as described by Sargent and Dawid (1983).

containing a restriction site) ligated to both sides. Both populations are then amplified by PCR, but the driver cDNA population is subsequently digested with the adaptor-containing restriction endonuclease. This serves to cleave the oligo-vector and reduce the amplification potential of the control population. The digested control population is then biotinylated and an excess mixed with tester cDNA. Following denaturation and hybridization, the mix is applied to a biocytin column (streptavidin may also be used) to remove the control population, including heteroduplexes formed by annealing of common sequences from the tester population. The procedure is repeated several times following the addition of fresh

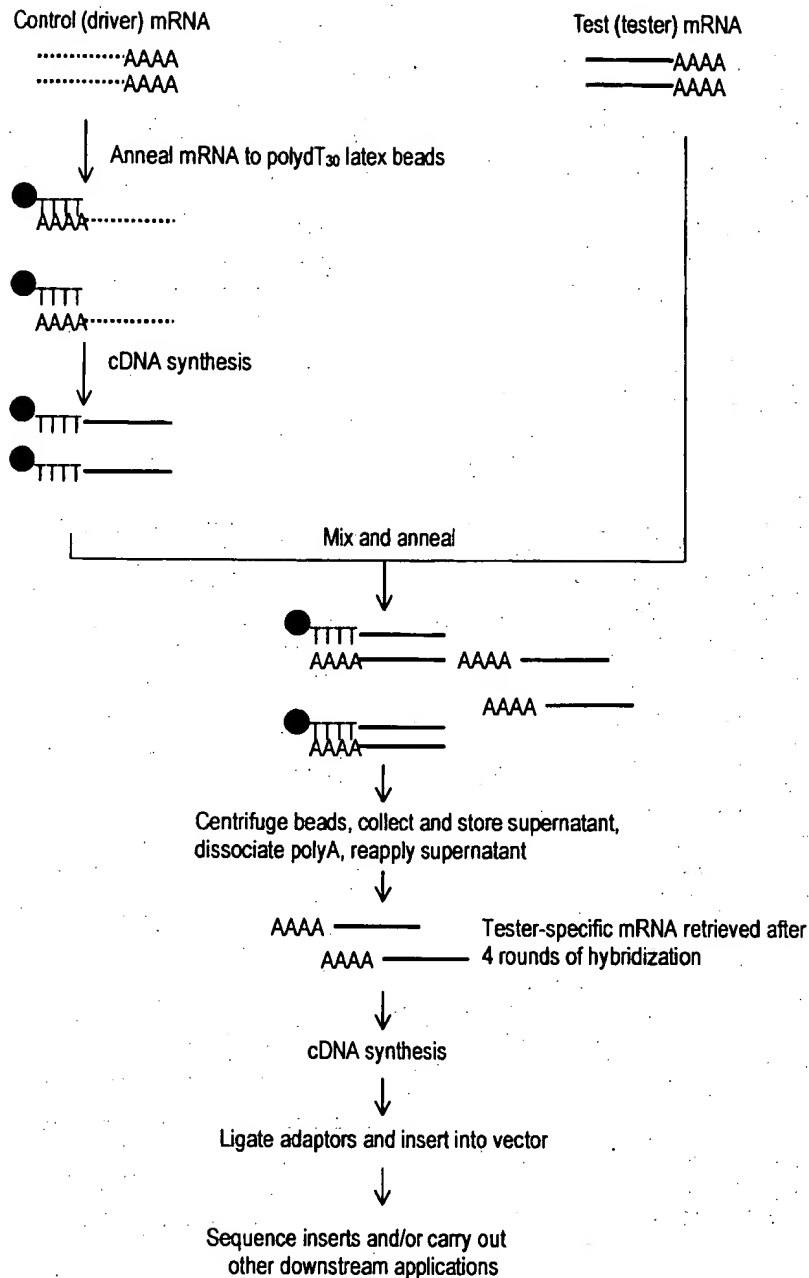


Figure 2. The use of oligodT<sub>30</sub> latex to perform subtractive hybridization. mRNA extracted from the control (driver) population is converted to anchored cDNA using polydT oligonucleotides attached to latex beads. mRNA from the treated/alterd (tester) population is repeatedly hybridized against an excess of the anchored driver cDNA. The final population of mRNA is tester specific and can be converted into cDNA for cloning and other downstream applications, as described by Hara *et al.* (1991).

control cDNA. In order to further enrich those species differentially expressed in the tester cDNA, the subtracted tester population is amplified by PCR following every second subtraction cycle. After six cycles of subtraction (three reamplification steps) the reaction mix is ligated into a vector for further analysis.

In a slightly different approach, Hara *et al.* (1991) utilized a method whereby oligo(dT<sub>30</sub>) primers attached to a latex substrate are used to first capture mRNA extracted from the control population. Following 1st strand cDNA synthesis, the RNA strand of the heteroduplexes is removed by heat denaturation and centrifugation (the cDNA-oligotex-dT<sub>30</sub> forms a pellet and the supernatant is removed). A quantity of tester mRNA is then repeatedly hybridized to the immobilized control (driver) cDNA (which is present in 20-fold excess). After several rounds of hybridization the only mRNA molecules left in the tester mRNA population are those which are not found in the driver cDNA-oligotex-dT<sub>30</sub> population. These tester-specific mRNA species are then converted to cDNA and, following the addition of adaptor sequences, amplified by PCR. The PCR products are then ligated into a vector for further analysis using restriction sites incorporated into the PCR primers. A schematic illustration of this subtraction process is shown in figure 2.

However, all these methods utilising physical separation have been described as inefficient due to the requirement for large starting amounts of mRNA, significant loss of material during the separation process and a need for several rounds of hybridization. Hence, new methods of differential expression analysis have recently been designed to eliminate these problems.

#### *Chemical Cross-Linking Subtraction (CCLS)*

In this technique, originally described by Hampson *et al.* (1992), driver mRNA is mixed with tester cDNA (1st strand only) in a ratio of > 20:1. The common sequences form cDNA:mRNA hybrids, leaving the tester specific species as single stranded cDNA. Instead of physically separating these hybrids, they are inactivated chemically using 2,5 diaziridinyl-1,4-benzoquinone (DZQ). Labelled probes are then synthesized from the remaining single stranded cDNA species (unreacted mRNA species remaining from the driver are not converted into probe material due to specificity of Sequenase T7 DNA polymerase used to make the probe) and used to screen a cDNA library made from the tester cell population. A schematic diagram of the system is shown in figure 3.

It has been shown that the differentially expressed sequences can be enriched at least 300-fold with one round of subtraction (Hampson *et al.* 1992), and that the technique should allow isolation of cDNAs derived from transcripts that are present at less than 50 copies per cell. This equates to genes at the low end of intermediate abundance (see table 1). The main advantages of the CCLS approach are that it is rapid, technically simple and also produces fewer false positives than other differential expression analysis methods. However, like the physical separation protocols, a major drawback with CCLS is the large amount of starting material required (at least 10 µg RNA). Consequently, the technique has recently been refined so that a renewable source of RNA can be generated. The degenerate random oligonucleotide primed (DROP) adaptation (Hampson *et al.* 1996, Hampson and Hampson 1997) uses random hexanucleotide sequences to prime solid phase-synthesized cDNA. Since each primer includes a T7 polymerase promoter sequence



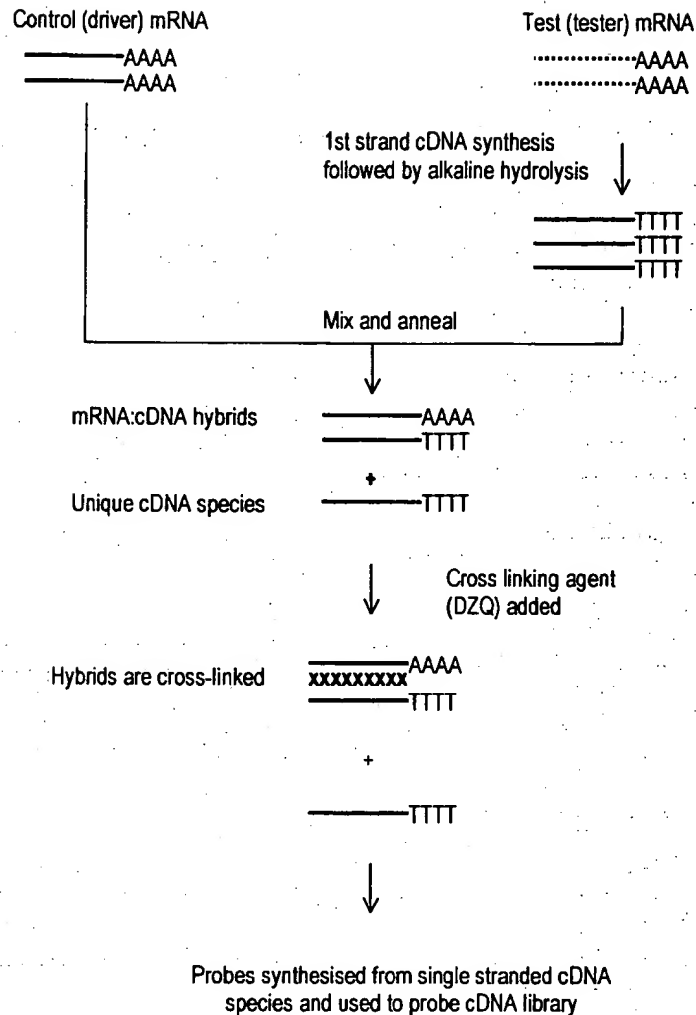


Figure 3. Chemical cross-linking subtraction. Excess driver mRNA is mixed with 1<sup>st</sup> strand tester cDNA. The common sequences form mRNA:cDNA hybrids which are cross linked with 2,5 diaziridinyl-1,4-benzoquinone (DZQ) and the remaining cDNA sequences are differentially expressed in the tester population. Probes are made from these sequences using Sequenase 2.0 DNA polymerase, which lacks reverse transcriptase activity and, therefore, does not react with the remaining mRNA molecules from the driver. The labelled probes are then used to screen a cDNA library for clones of differentially expressed sequences. Adapted from Walter *et al.* (1996), with permission.

Table 1. The abundance of mRNA species and classes in a typical mammalian cell.

mRNA class	Copies of each species/cell	No. of mRNA species in class	Mean % of each species in class	Mean mass (ng) of each species/ $\mu$ g total RNA
Abundant	12000	4	3.3	1.65
Intermediate	300	500	0.08	0.04
Rare	15	11000	0.004	0.002

Modified from Bertioli *et al.* (1995).

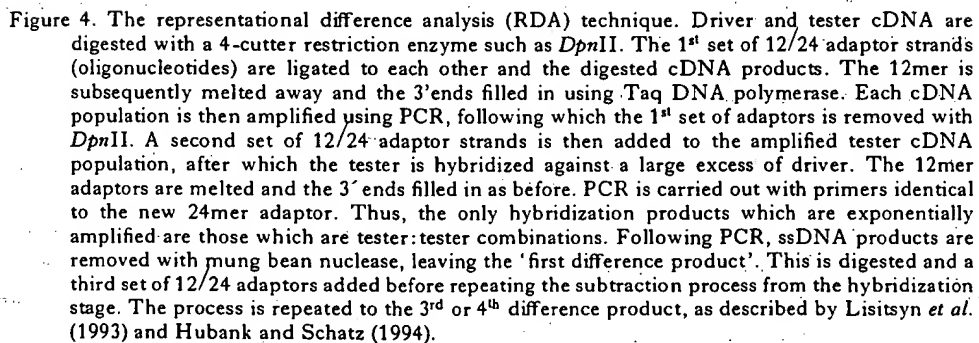
at the 5' end, the final pool of random cDNA fragments is a PCR-renewable cDNA population which is representative of the expressed gene pool and can be used to synthesize sense RNA for use as driver material. Furthermore, if the final pool of random cDNA fragments is reamplified using biotinylated T7 primer and random hexamer, the product can be captured with streptavidin beads and the antisense strand eluted for use as tester. Since both target and driver can be generated from the same DROP product, subtraction can be performed in both directions (i.e. for up- and down-regulated species) between two different DROP products.

#### *Representational Difference Analysis (RDA)*

RDA of cDNA (Hubank and Schatz 1994) is an extension of the technique originally applied to genomic DNA as a means of identifying differences between two complex genomes (Lisitsyn *et al.* 1993). It is a process of subtraction and amplification involving subtractive hybridization of the tester in the presence of excess driver. Sequences in the tester that have homologues in the driver are rendered unamplifiable, whereas those genes expressed only in the tester retain the ability to be amplified by PCR. The procedure is shown schematically in figure 4.

In essence, the driver and tester mRNA populations are first converted to cDNA and amplified by PCR following the ligation of an adaptor. The adaptors are then removed from both populations and a new (different) adaptor ligated to the amplified tester population only. Driver and tester populations are next melted and hybridized together in a ratio of 100:1. Following hybridization, only tester:tester homohybrids have 5' adaptors at each end of the DNA duplex and can, thus, be filled in at both 3' ends. Hence, only these molecules are amplified exponentially during the subsequent PCR step. Although tester:driver heterohybrids are present, they only amplify in a linear fashion, since the strand derived from the driver has no adaptor to which the primer can bind. Driver:driver heterohybrids have no adaptors and, therefore, are not amplified. Single stranded molecules are digested with mung bean nuclease before a further PCR-enrichment of the tester:tester homohybrids. The adaptors on the amplified tester population are then replaced and the whole process repeated a further two or three times using an increasing excess of driver (Hubank and Schatz used a tester:driver ratio of 1:400, 1:80000 and 1:800000 for the second, third and fourth hybridizations, respectively). Different adaptors are ligated to the tester between successive rounds of hybridization and amplification to prevent the accumulation of PCR products that might interfere with subsequent amplifications. The final display is a series of differentially expressed gene products easily observable on an ethidium bromide gel.

The main advantages of RDA are that it offers a reproducible and sensitive approach to the analysis of differentially expressed genes. Hubank and Schatz (1994) reported that they were able to isolate genes that were differentially expressed in substantially less than 1% of the cells from which the tester is derived. Perhaps the main drawback is that multiple rounds of ligation, hybridization, amplification and digestion are required. The procedure is, therefore, lengthier than many other differential display approaches and provides more opportunity for operator-induced error to occur. Although the generation of false positives has been noted, this has been solved to some degree by O'Neill and Sinclair (1997) through the use of HPLC-purified adaptors. These are free of the truncated adaptors which appear to be a major source of the false positive bands. A very similar technique to RDA, termed linker capture subtraction (LCS) was described by Yang and Sytowski (1996).



### *Suppression PCR Subtractive Hybridization (SSH)*

The most recent adaptation of the SH approach to differential expression analysis was first described by Diatchenko *et al.* (1996) and Gurskaya *et al.* (1996). They reported that a 1000–5000 fold enrichment of rare cDNAs (equivalent to isolating mRNAs present at only a few copies per cell) can be obtained without the need for multiple hybridizations/subtractions. Instead of physical or chemical removal of the common sequences, a PCR-based suppression system is used (see figure 5).

In SSH, excess driver cDNA is added to two portions of the tester cDNA which have been ligated with different adaptors. A first round of hybridization serves to enrich differentially expressed genes and equalize rare and abundant messages. Equalization occurs since reannealing is more rapid for abundant molecules than for rarer molecules due to the second order kinetics of hybridization (James and Higgins 1985). The two primary hybridization mixes are then mixed together in the presence of excess driver and allowed to hybridize further. This step permits the annealing of single stranded complementary sequences which did not hybridize in the primary hybridization, and in doing so generates templates for PCR amplification. Although there are several possible combinations of the single stranded molecules present in the secondary hybridization mix, only one particular combination (differentially expressed in the tester cDNA composed of complimentary strands having different adaptors) can amplify exponentially.

Having obtained the final differential display, two options are available if cloning of cDNAs is desired. One is to transform the whole of the final PCR reaction into competent cells. Transformed colonies can then be isolated and their inserts characterized by sequencing, restriction analysis or PCR. Alternatively, the final PCR products can be resolved on a gel and the individual bands excised, reamplified and cloned. The first approach is technically simpler and less time consuming. However, ligation/transformation reactions are known to be biased towards the cloning of smaller molecules, and so the final population of clones will probably not contain a representative selection of the larger products. In addition, although equalization theoretically occurs, observations in this laboratory suggest that this is by no means perfectly accomplished. Consequently, some gene species are present in a higher number than others and this will be represented in the final population of clones. Thus, in order to obtain a substantial proportion of those gene species that actually demonstrate differential expression in the tester population, the number of clones that will have to be screened after this step may be substantial. The second approach is initially more time consuming and technically demanding. However, it would appear to offer better prospects for cloning larger and low abundance gel products. In addition, one can incorporate a screening step that differentiates different products of different sequences but of the same size (HA-staining, see later). In this way, a good idea of the final number of clones to be isolated and identified can be achieved.

An alternative (or even complementary) approach is to use the final differential display reaction to screen a cDNA library to isolate full length clones for further characterization, or a DNA array (see later) to quickly identify known genes. SSH has been used in this laboratory to begin characterization of the short-term gene expression profiles of enzyme-inducers such as phenobarbital (Rockett *et al.* 1997) and Wy-14,643 (Rockett *et al.* unpublished observations). The isolation of differentially expressed genes in this manner enables the construction of a fingerprint

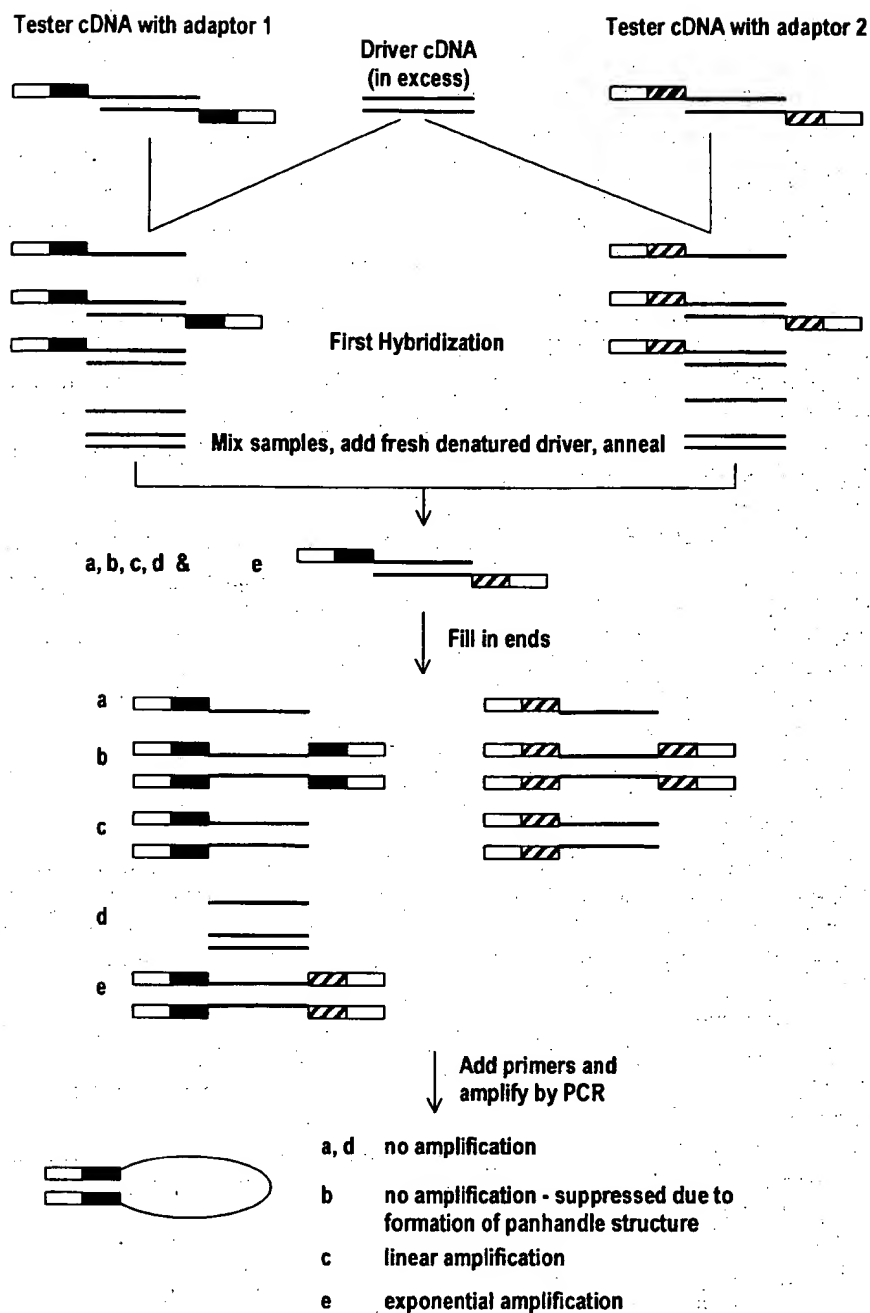


Figure 5. PCR-select cDNA subtraction. In the primary hybridization, an excess of driver cDNA is added to each tester cDNA population. The samples are heat denatured and allowed to hybridize for between 3 and 8 h. This serves two purposes: (1) to equalize rare and abundant molecules; and (2) to enrich for differentially expressed sequences—cDNAs that are not differentially expressed form type c molecules with the driver. In the secondary hybridization, the two primary hybridizations are mixed together without denaturing. Fresh denatured driver can also be added at this point to allow further enrichment of differentially expressed sequences. Type e molecules are formed in this secondary hybridization which are subsequently amplified using two rounds of PCR. The final products can be visualized on an agarose gel, labelled directly or cloned into a vector for downstream manipulation. As described by Diatchenko *et al.* (1996) and Gurskaya *et al.* (1996), with permission.

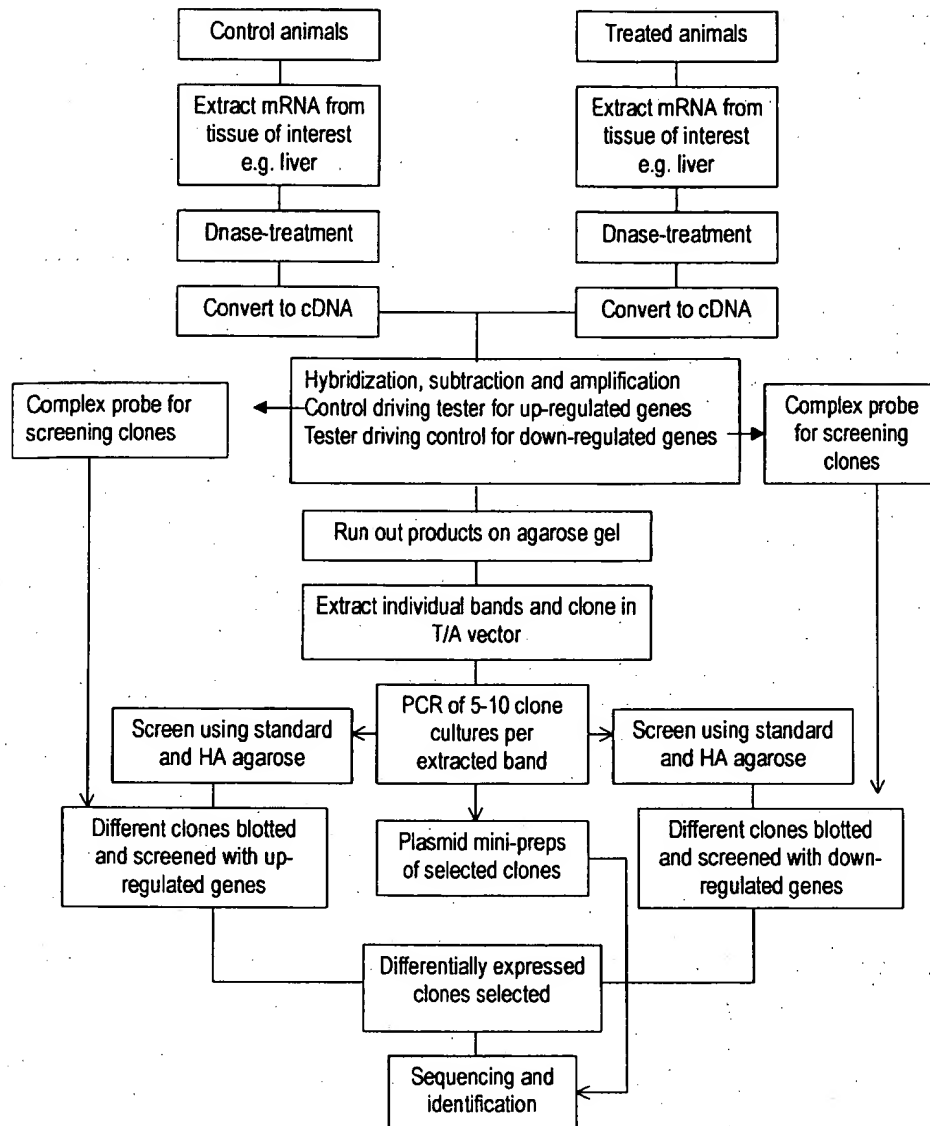


Figure 6. Flow diagram showing method used in this laboratory to isolate and identify clones of genes which are differentially expressed in rat liver following short term exposure to the enzyme inducers, phenobarbital and Wy-14,643.

of expressed genes which are unique to each compound and time/dose point. Such information could be useful in short-term characterization of the toxic potential of new compounds by comparing the gene-expression profiles they elicit with those produced by known inducers. Figure 6 shows a flow diagram of the method used to isolate, verify and clone differentially expressed genes, and figure 7 shows expression profiles obtained from a typical SSH experiment. Subsequent sub-cloning of the individual bands, sequencing and gene data base interrogation reveals many genes which are either up- or down-regulated by phenobarbital in the rat (tables 2 and 3).

One of the advantages in using the SSH approach is that no prior knowledge is required of which specific genes are up/down-regulated subsequent to xenobiotic

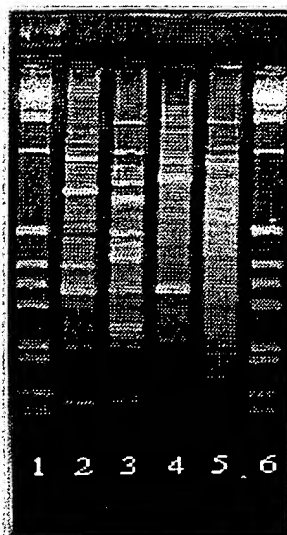


Figure 7. SSH display patterns obtained from rat liver following 3-day treatment with WY-14,643 or phenobarbital. mRNA extracted from control and treated livers was used to generate the differential displays using the PCR-Select cDNA subtraction kit (Clontech). Lane: 1—1kb ladder; 2—genes upregulated following Wy,14-643 treatment; 3—genes downregulated following Wy,14-643 treatment; 4—genes upregulated following phenobarbital treatment; 5—genes downregulated following phenobarbital treatment; 6—1kb ladder. Reproduced from Rockett *et al.* (1997), with permission.

exposure, and an almost complete complement of genes are obtained. For example, the peroxisome proliferator and non-genotoxic hepatocarcinogen Wy,14,643, up-regulates at least 28 genes and down-regulates at least 15 in the rat (a sensitive species) and produces 48 up- and 37 down-regulated genes in the guinea pig, a resistant species (Rockett, Swales, Esda and Gibson, unpublished observations). One of these genes, CD81, was up-regulated in the rat and down-regulated in the guinea pig following Wy-14,643 treatment. CD81 (alternatively named TAPA-1) is a widely expressed cell surface protein which is involved in a large number of cellular processes including adhesion, activation, proliferation and differentiation (Levy *et al.* 1998). Since all of these functions are altered to some extent in the phenomena of hepatomegaly and non-genotoxic hepatocarcinogenesis, it is intriguing, and probably mechanistically-relevant, that CD81 expression is differentially regulated in a resistant and susceptible species. However, the down-side of this approach is that the majority of genes can be sequenced and matched to database sequences, but the latter are predominantly expressed sequence tags or genes of completely unknown function, thus partially obscuring a realistic overall assessment of the critical genes of genuine biological interest. Notwithstanding the lack of complete functional identification of altered gene expression, such gene profiling studies essentially provides a 'molecular fingerprint' in response to xenobiotic challenge, thereby serving as a mechanistically-relevant platform for further detailed investigations.

#### Differential Display (DD)

Originally described as 'RNA fingerprinting by arbitrarily primed PCR' (Liang and Pardee 1992) this method is now more commonly referred to as 'differential

Table 2. Genes up-regulated in rat liver following 3-day exposure to phenobarbital.

Band number (approximate size in bp)	Highest sequence similarity	FASTA-EMBL gene identification
5 (1300)	93.5%	CYP2B1
7 (1000)	95.1%	Preproalbumin Serum albumin mRNA
8 (950)	98.3%	NCI-CGAP-Pr1 <i>H. sapiens</i> (EST)
10 (850)	95.7%	CYP2B1
11 (800)	Clone 1 94.9%	CYP2B1
	Clone 2 75.3%	CYP2B2
12 (750)	93.8%	TRPM-2 mRNA
15 (600)	92.9%	Sulfated glycoprotein Preproalbumin Serum albumin mRNA
16 (55)	Clone 1 95.2%	CYP2B1
	Clone 2 93.6%	Haptoglobulin mRNA partial alpha
21 (350)	99.3%	18S, 5.8S & 28S rRNA

Bands 1–4, 6, 9, 13, 14, and 17–20 are shown to be false positives by dot blot analysis and, therefore, are not sequenced. Derived from Rockett *et al.* (1997). It should be noted that the above genes do not represent the complete spectrum of genes which are up-regulated in rat liver by phenobarbital, but simply represents the genes sequenced and identified to date.

Table 3. Genes down-regulated in rat liver following 3-day exposure to phenobarbital.

Band number (approximate size in bp)	Highest sequence similarity	FASTA-EMBL gene identification
1 (1500)	95.3%	3-oxoacyl-CoA thiolase
2 (1200)	92.3%	Hemopexin mRNA
3 (1000)	91.7%	Alpha-2u-globulin mRNA
7 (700)	Clone 1 77.2%	<i>M. musculus</i> C1 inhibitor
	Clone 2 94.5%	Electron transfer flavoprotein
	Clone 3 91.0%	<i>M. musculus</i> Topoisomerase 1 (Topo 1)
8 (650)	Clone 1 86.9%	Soares 2NbMT <i>M. musculus</i> (EST)
	Clone 2 96.2%	Alpha-2u-globulin (s-type) mRNA
9 (600)	Clone 1 86.9%	Soares mouse NML <i>M. musculus</i> (EST)
	Clone 2 82.0%	Soares p3NMF 19.5 <i>M. musculus</i> (EST)
10 (550)	73.8%	Soares mouse NML <i>M. musculus</i> (EST)
11 (525)	95.7%	NCI-CGAP-Pr1 <i>H. sapiens</i> (EST)
12 (375)	100.0%	Ribosomal protein
13 (23)	Clone 1 97.2%	Soares mouse embryo NbME135 (EST)
	Clone 2 100.0%	Fibrinogen B-beta-chain
	Clone 3 100.0%	Apolipoprotein E gene
14 (170)	96.0%	Soares p3NMF19.5 <i>M. musculus</i> (EST)
15 (140)	97.3%	Stratagene mouse testis (EST)
Others: (300)	96.7%	<i>R. norvegicus</i> RASP 1 mRNA
(275)	93.1%	Soares mouse mammary gland (EST)

EST = Expressed sequence tag. Bands 4–6 were shown to be false positives by dot blot analysis and, therefore, were not sequenced. Derived from Rockett *et al.* (1997). It should be noted that the above genes do not represent the complete spectrum of genes which are down-regulated in rat liver by phenobarbital, but simply represents the genes sequenced and identified to date.

display' (DD). In this method, all the mRNA species in the control and treated cell populations are amplified in separate reactions using reverse transcriptase-PCR (RT-PCR). The products are then run side-by-side on sequencing gels. Those bands which are present in one display only, or which are much more intense in one



display compared to the other, are differentially expressed and may be recovered for further characterization. One advantage of this system is the speed with which it can be carried out—2 days to obtain a display and as little as a week to make and identify clones.

Two commonly used variations are based on different methods of priming the reverse transcription step (figure 8). One is to use an oligo dT with a 2-base 'anchor' at the 3'-end, e.g. 5' (dT<sub>11</sub>)CA 3' (Liang and Pardee 1992). Alternatively, an arbitrary primer may be used for 1st strand cDNA synthesis (Welsh *et al.* 1992). This variant of RNA fingerprinting has also been called 'RAP' (RNA Arbitrarily Primed)-PCR. One advantage of this second approach is that PCR products may be derived from anywhere in the RNA, including open reading frames. In addition, it can be used for mRNAs that are not polyadenylated, such as many bacterial mRNAs (Wong and McClelland 1994). In both cases, following reverse transcription and denaturation, second strand cDNA synthesis is carried out with an arbitrary primer (*arbitrary* primers have a single base at each position, as compared to *random* primers, which contain a mixture of all four bases at each position). The resulting PCR, thus, produces a series of products which, depending on the system (primer length and composition, polymerase and gel system), usually includes 50–100 products per primer set (Band and Sager 1989). When a combination of different dT-anchors and arbitrary primers are used, almost all mRNA species from a cell can be amplified. When the cDNA products from two different populations are analysed side by side on a polyacrylamide gel, differences in expression can be identified and the appropriate bands recovered for cloning and further analysis.

Although DD is perhaps the most popular approach used today for identifying differentially expressed genes, it does suffer from several perceived disadvantages:

- (1) It may have a strong bias towards high copy number mRNAs (Bertioli *et al.* 1995), although this has been disputed (Wan *et al.* 1996) and the isolation of very low abundance genes may be achieved in certain circumstances (Guimeraes *et al.* 1995a).
- (2) The cDNAs obtained often only represent the extreme 3' end of the mRNA (often the 3'-untranslated region), although this may not always be the case (Guimeraes *et al.* 1995a). Since the 3' end is often not included in Genbank and shows variation between organisms, cDNAs identified by DD cannot always be matched with their genes, even if they have been identified.
- (3) The pattern of differential expression seen on the display often cannot be reproduced on Northern blots, with false positives arising in up to 70% of cases (Sun *et al.* 1994). Some adaptations have been shown to reduce false positives, including the use of two reverse transcriptases (Sung and Denman 1997), comparison of uninduced and induced cells over a time course (Burn *et al.* 1994) and comparison of DDPCR-products from two uninduced and two induced lines (Sompayrac *et al.* 1995). The latter authors also reported that the use of cytoplasmic RNA rather than total RNA reduces false positives arising from nuclear RNA that is not transported to the cytoplasm.

Further details of the background, strengths and weaknesses of the DD technique can be obtained from a review by McClelland *et al.* (1996) and from articles by Liang *et al.* (1995) and Wan *et al.* (1996).

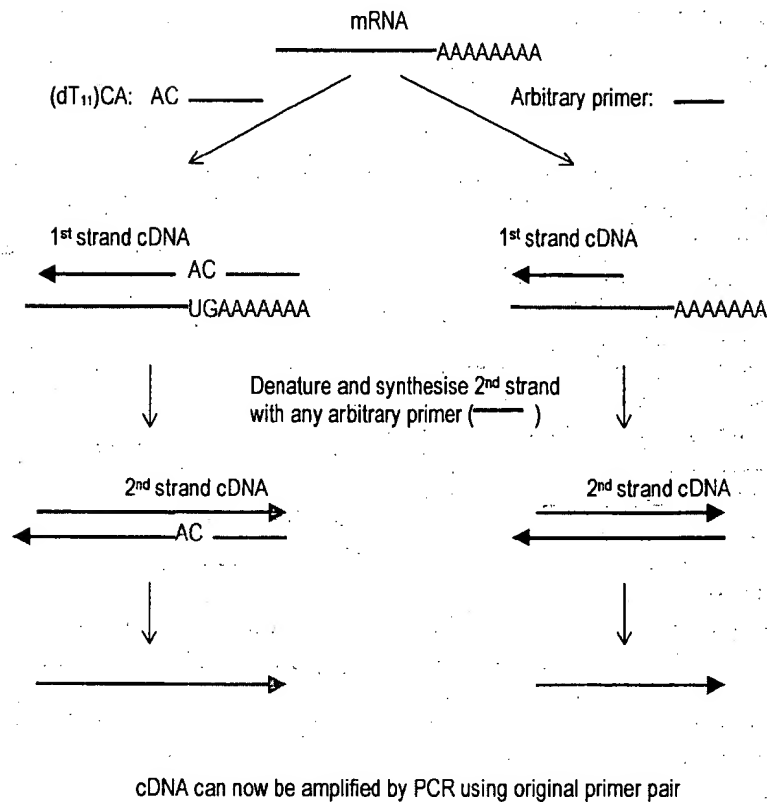


Figure 8. Two approaches to differential display (DD) analysis. 1<sup>st</sup> strand synthesis can be carried out either with a polydT<sub>11</sub>NN primer (where N = G, C or A) or with an arbitrary primer. The use of different combinations of G, C and A to anchor the first strand polydT primer enables the priming of the majority of polyadenylated mRNAs. Arbitrary primers may hybridize at none, one or more places along the length of the mRNA, allowing 1<sup>st</sup> strand cDNA synthesis to occur at none, one or more points in the same gene. In both cases, 2<sup>nd</sup> strand synthesis is carried out with an arbitrary primer. Since these arbitrary primers for the 2<sup>nd</sup> strand may also hybridize to the 1<sup>st</sup> strand cDNA in a number of different places, several different 2<sup>nd</sup> strand products may be obtained from one binding point of the 1<sup>st</sup> strand primer. Following 2<sup>nd</sup> strand synthesis, the original set of primers is used to amplify the second strand products, with the result that numerous gene sequences are amplified.

### Restriction endonuclease-facilitated analysis of gene expression

#### *Serial Analysis of Gene Expression (SAGE)*

A more recent development in the field of differential display is SAGE analysis (Velculescu *et al.* 1995). This method uses a different approach to those discussed so far and is based on two principles. Firstly, in more than 95% of cases, short nucleotide sequences ('tags') of only nine or 10 base pairs provide sufficient information to identify their gene of origin. Secondly, concatenation (linking together in a series) of these tags allows sequencing of multiple cDNAs within a single clone. Figure 9 shows a schematic representation of the SAGE process. In this procedure, double stranded cDNA from the test cells is synthesized with a biotinylated polydT primer. Following digestion with a commonly cutting (4bp recognition sequence) restriction enzyme ('anchoring enzyme'), the 3' ends of the cDNA population are captured with streptavidin beads. The captured population is

split into two and different adaptors ligated to the 5' ends of each group. Incorporated into the adaptors is a recognition sequence for a type IIS restriction enzyme—one which cuts DNA at a defined distance (< 20 bp) from its recognition sequence. Hence, following digestion of each captured cDNA population with the IIS enzyme, the adaptors plus a short piece of the captured cDNA are released. The two populations are then ligated and the products amplified. The amplified products are cleaved with the original anchoring enzyme, religated (concatomers are formed in the process) and cloned. The advantage of this system is that hundreds of gene tags can be identified by sequencing only a few clones. Furthermore, the number of times a given transcript is identified is a quantitative measurement of that gene's abundance in the original population, a feature which facilitates identification of differentially expressed genes in different cell populations.

Some disadvantages of SAGE analysis include the technical difficulty of the method, a large amount of accurate sequencing is required, biased towards abundant mRNAs, has not been validated in the pharmaco/toxicogenomic setting and has only been used to examine well known tissue differences to date.

#### *Gene Expression Fingerprinting (GEF)*

A different capture/restriction digest approach for isolating differentially expressed genes has been described by Ivanova and Belyavsky (1995). In this method, RNA is converted to cDNA using biotinylated oligo(dT) primers. The cDNA population is then digested with a specific endonuclease and captured with magnetic streptavidin microbeads to facilitate removal of the unwanted 5' digestion products. The use of restricted 3'-ends alone serves to reduce the complexity of the cDNA fragment pool and helps to ensure that each RNA species is represented by not more than one restriction product. An adaptor is ligated to facilitate subsequent amplification of the captured population. PCR is carried out with one adaptor-specific and one biotinylated polydT primer. The reamplified population is recaptured and the non-biotinylated strands removed by alkaline dissociation. The non-biotinylated strand is then resynthesized using a different adaptor-specific primer in the presence of a radiolabelled dNTP. The labelled immobilized 3' cDNA ends are next sequentially treated with a series of different restriction endonucleases and the products from each digestion analysed by PAGE. The result is a fingerprint composed of a number of ladders (equal to the number of sequential digests used). By comparing test versus control fingerprints, it is possible to identify differentially expressed products which can then be isolated from the gel and cloned. The advantages of this procedure are that it is very robust and reproducible, and the authors estimate that 80–93% of cDNA molecules are involved in the final fingerprint. The disadvantage is that polyacrylamide gels can rarely resolve more than 300–400 bands, which compares poorly to the 1000 or more which are estimated to be produced in an average experiment. The use of 2-D gels such as those described by Uitterlinden *et al.* (1989) and Hatada *et al.* (1991) may help to overcome this problem.

A similar method for displaying restriction endonuclease fragments was later described by Prashar and Weissman (1996). However, instead of sequential digestion of the immobilized 3'-terminal cDNA fragments, these authors simply compared the profiles of the control and treated populations without further manipulation.

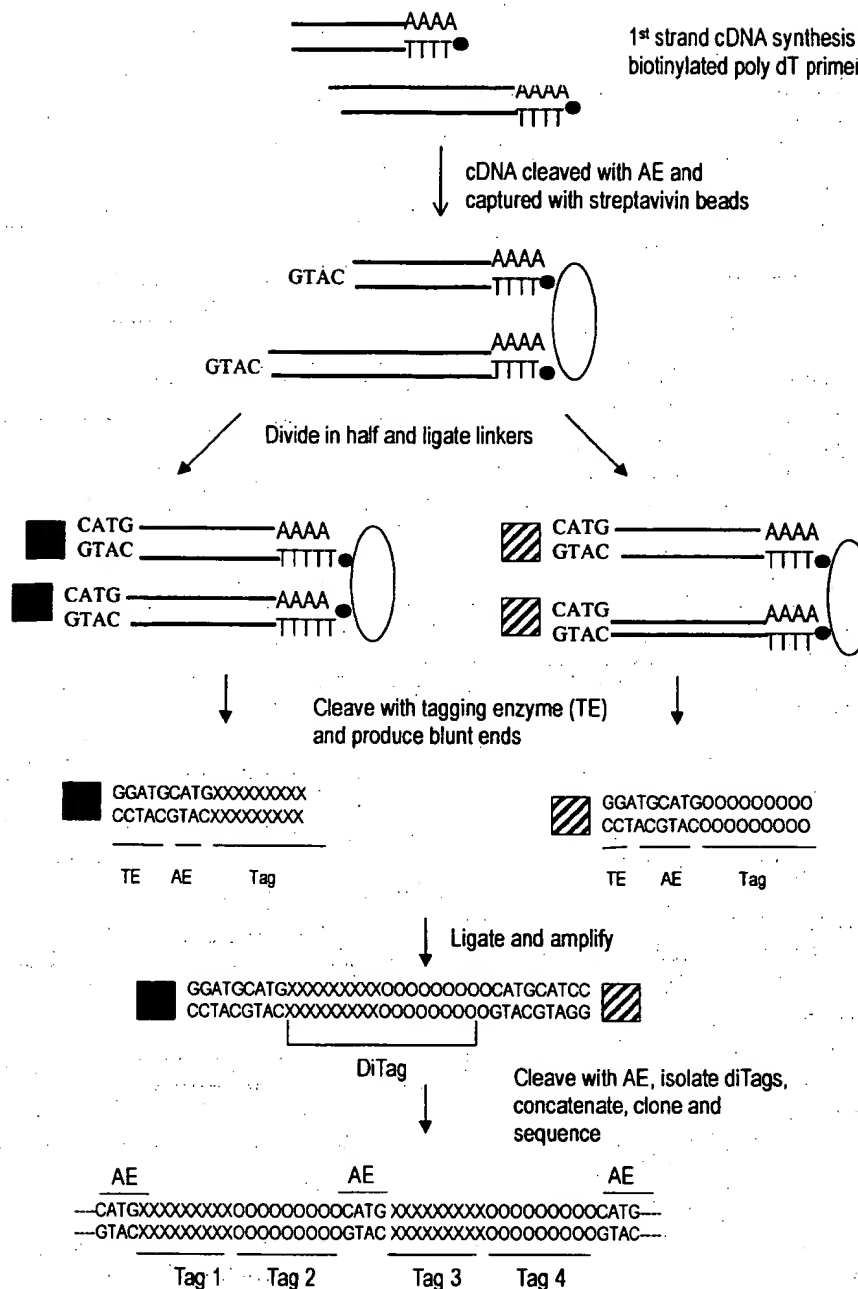


Figure 9. Serial analysis of gene expression (SAGE) analysis. cDNA is cleaved with an anchoring enzyme (AE) and the 3' ends captured using streptavidin beads. The cDNA pool is divided in half and each portion ligated to a different linker, each containing a type IIS restriction site (tagging enzyme, TE). Restriction with the type IIS enzyme releases the linker plus a short length of cDNA (XXXXXX and OOOOO indicate nucleotides of different tags). The two pools of tags are then ligated and amplified using linker-specific primers. Following PCR, the products are cleaved with the AE and the diTags isolated from the linkers using PAGE. The diTags are then ligated (during which process, concatenation occurs) and cloned into a vector of choice for sequencing. After Velculescu *et al.* (1995), with permission.

### DNA arrays

'Open' differential display systems are cumbersome in that it takes a great deal of time to extract and identify candidate genes and then confirm that they are indeed up- or down-regulated in the treated compared to the control tissue. Normally, the latter process is carried out using Northern blotting or RT-PCR. Even so, each of the aforementioned steps produce a bottleneck to the ultimate goal of rapid analysis of gene expression. These problems will likely be addressed by the development of so-called DNA arrays (e.g. Gress *et al.* 1992, Zhao *et al.* 1995, Schena *et al.* 1996), the introduction of which has signalled the next era in differential gene expression analysis. DNA arrays consist of a gridded membrane or glass 'chips' containing hundreds or thousands of DNA spots, each consisting of multiple copies of part of a known gene. The genes are often selected based on previously proven involvement in oncogenesis, cell cycling, DNA repair, development and other cellular processes. They are usually chosen to be as specific as possible for each gene and animal species. Human and mouse arrays are already commercially available and a few companies will construct a personalized array to order, for example Clontech Laboratories and Research Genetics Inc. The technique is rapid in that hundreds or even thousands of genes can be spotted on a single array, and that mRNA/cDNA from the test populations can be labelled and used directly as probe. When analysed with appropriate hardware and software, arrays offer a rapid and quantitative means to assess differences in gene expression between two cell populations. Of course, there can only be identification and quantitation of those genes which are in the array (hence the term 'closed' system). Therefore, one approach to elucidating the molecular mechanisms involved in a particular disease/development system may be to combine an open and closed system—a DNA array to directly identify and quantitate the expression of known genes in mRNA populations, and an open system such as SSH to isolate unknown genes which are differentially expressed.

One of the main advantages of DNA arrays is the huge number of gene fragments which can be put on a membrane—some companies have reported gridding up to 60000 spots on a single glass 'chip' (microscope slide). These high density chip-based micro-arrays will probably become available as mass-produced off-the-shelf items in the near future. This should facilitate the more rapid determination of differential expression in time and dose-response experiments. Aside from their high cost and the technical complexities involved in producing and probing DNA arrays, the main problem which remains, especially with the newer micro-array (gene-chip) technologies, is that results are often not wholly reproducible between arrays. However, this problem is being addressed and should be resolved within the next few years.

### EST databases as a means to identify differentially expressed genes

Expressed sequence tags (ESTs) are partial sequences of clones obtained from cDNA libraries. Even though most ESTs have no formal identity (putative identification is the best to be hoped for), they have proven to be a rapid and efficient means of discovering new genes and can be used to generate profiles of gene-expression in specific cells. Since they were first described by Adams *et al.* (1991), there has been a huge explosion in EST production and it is estimated that there are now well over a million such sequences in the public domain, representing over half

of all human genes (Hillier *et al.* 1996). This large number of freely available sequences (both sequence information and clones are normally available royalty-free from the originators) has enabled the development of a new approach towards differential gene expression analysis as described by Vasmatazis *et al.* (1998). The approach is simple in theory: EST databases are first searched for genes that have a number of related EST sequences from the target tissue of choice, but none or few from non-target tissue libraries. Programmes to assist in the assembly of such sets of overlapping data may be developed in-house or obtained privately or from the internet. For example, the Institute for Genomic Research (TIGR, found at <http://www.tigr.org>) provides many software tools free of charge to the scientific community. Included amongst these is the TIGR assembler (Sutton *et al.* 1995), a tool for the assembly of large sets of overlapping data such as ESTs, bacterial artificial chromosomes (BAC)s, or small genomes. Candidate EST clones representing different genes are then analysed using RNA blot methods for size and tissue specificity and, if required, used as probes to isolate and identify the full length cDNA clone for further characterization. In practice however, the method is rather more involved, requiring bioinformatic and computer analysis coupled with confirmatory molecular studies. Vasmatazis *et al.* (1998) have described several problems in this fledgling approach, such as separating highly homologous sequences derived from different genes and an overemphasis of specificity for some EST sequences. However, since these problems will largely be addressed by the development of more suitable computer algorithms and an increased completeness of the EST database, it is likely that this approach to identifying differentially expressed genes may enjoy more patronage in the future.

### Problems and potential of differential expression techniques

#### *The holistic or single cell approach?*

When working with *in vivo* models of differential expression, one of the first issues to consider must be the presence of multiple cell types in any given specimen. For example, a liver sample is likely to contain not only hepatocytes, but also (potentially) Ito cells, bile ductule cells, endothelial cells, various immune cells (e.g. lymphocytes, macrophages and Kupffer cells) and fibroblasts. Other tissues will each have their own distinctive cell populations. Also, in the case of neoplastic tissue, there are almost always normal, hyperplastic and/or dysplastic cells present in a sample. One must, therefore, be aware that genes obtained from a differential display experiment performed on an animal tissue model may not necessarily arise exclusively from the intended 'target' cells, e.g. hepatocytes/neoplastic cells. If appropriate, further analyses using immunohistochemistry, *in situ* hybridization or *in situ* RT-PCR should be used to confirm which cell types are expressing the gene(s) of interest. This problem is probably most acute for those studying the differential expression of genes in the development of different cell types, where there is a need to examine homologous cell populations. The problem is now being addressed at the National Cancer Institute (Bethesda, MD, USA) where new microdissection techniques have been employed to assist in their gene analysis programme, the Cancer Genome Anatomy Project (CGAP) (For more information see web site: <http://www.ncbi.nlm.nih.gov/ncicgap/intro.html>). There are also separation techniques available that utilise cell-specific antigens as a means to isolate target cells,

e.g. fluorescence activated cell sorting (FACS) (Dunbar *et al.* 1998, Kas-Deelen *et al.* 1998) and magnetic bead technology (Richard *et al.* 1998, Rogler *et al.* 1998).

However, those taking a holistic approach may consider this issue unimportant. There is an equally appropriate view that all those genes showing altered expression within a compromised tissue should be taken into consideration. After all, since all tissues are complex mixes of different, interacting cell types which intimately regulate each other's growth and development, it is clear that each cell type could in some way contribute (positively or negatively) towards the molecular mechanisms which lie behind responses to external stimuli or neoplastic growth. It is perhaps then more informative to carry out differential display experiments using *in vivo* as opposed to *in vitro* models, where uniform populations of identical cells probably represent a partial, skewed or even inaccurate picture of the molecular changes that occur.

The incidence and possible implications of inter-individual biological variation should be considered in any approach where whole animal models are being used. It is clear that individuals (humans and animals) respond in different ways to identical stimuli. One of the best characterized examples is the debrisoquine oxidation polymorphism, which is mediated by cytochrome CYP2D6 and determines the pharmacokinetics of many commonly prescribed drugs (Lennard 1993, Meyer and Zanger 1997). The reasons for such differences are varied and complex, but allelic variations, regulatory region polymorphisms and even physical and mental health can all contribute to observed differences in individual responses. Careful thought should, therefore, be given to the specific objectives of the study and to the possible value of pooling starting material (tissue/mRNA). The effect of this can be beneficial through the ironing out of exaggerated responses and unimportant minor fluctuations of (mechanistically) irrelevant genes in individual animals, thus providing a clearer overall picture of the general molecular mechanisms of the response. However, at the same time such minor variations may be of utmost importance in deciding the ability of individual animals to succumb to or resist the effects of a given chemical/disease.

*How efficient are differential expression techniques at recovering a high percentage of differentially expressed genes?*

A number of groups have produced experimental data suggesting that mammalian cells produce between 8000–15000 different mRNA species at any one time (Mechler and Rabbitts 1981, Hedrick *et al.* 1984, Bravo 1990), although figures as high as 20–30000 have also been quoted (Axel *et al.* 1976). Hedrick *et al.* (1984) provided evidence suggesting that the majority of these belong to the rare abundance class. A breakdown of this abundance distribution is shown in table 1.

When the results of differential display experiments have been compared with data obtained previously using other methods, it is apparent that not all differentially expressed mRNAs are represented in the final display. In particular, rare messages (which, importantly, often include regulatory proteins) are not easily recovered using differential display systems. This is a major shortcoming, as the majority of mRNA species exist at levels of less than 0.005% of the total population (table 1). Bertioli *et al.* (1995) examined the efficiency of DD templates (heterogeneous mRNA populations) for recovering rare messages and were unable to detect mRNA

species present at less than 1.2% of the total mRNA population—equivalent to an intermediate or abundant species. Interestingly, when simple model systems (single target only) were used instead of a heterogeneous mRNA population, the same primers could detect levels of target mRNA down to 10000× smaller. These results are probably best explained by competition for substrates from the many PCR products produced in a DD reaction.

The numbers of differentially expressed mRNAs reported in the literature using various model systems provides further evidence that many differentially expressed mRNAs are not recovered. For example, DeRisi *et al.* (1997) used DNA array technology to examine gene expression in yeast following exhaustion of sugar in the medium, and found that more than 1700 genes showed a change in expression of at least 2-fold. In light of such a finding, it would not be unreasonable to suggest that of the 8000–15 000 different mRNA species produced by any given mammalian cell, up to 1000 or more may show altered expression following chemical stimulation. Whilst this may be an extreme figure, it is known that at least 100 genes are activated/upregulated in Jurkat (T-) cells following IL-2 stimulation (Ullman *et al.* 1990). In addition, Wan *et al.* (1996) estimated that interferon- $\gamma$ -stimulated HeLa cells differentially express up to 433 genes (assuming 24000 distinct mRNAs expressed by the cells). However, there have been few publications documenting anywhere near the recovery of these numbers. For example, in using DD to compare normal and regenerating mouse liver, Bauer *et al.* (1993) found only 70 of 38000 total bands to be different. Of these, 50% (35 genes) were shown to correspond to differentially expressed bands. Chen *et al.* (1996) reported 10 genes upregulated in female rat liver following ethinyl estradiol treatment. McKenzie and Drake (1997) identified 14 different gene products whose expression was altered by phorbol myristate acetate (PMA, a tumour promoter agent) stimulation of a human myelomonocytic cell line. Kilty and Vickers (1997) identified 10 different gene products whose expression was upregulated in the peripheral blood leukocytes of allergic disease sufferers. Linskens *et al.* (1995) found 23 genes differentially expressed between young and senescent fibroblasts. Techniques other than DD have also provided an apparent paucity of differentially expressed genes. Using SH for example, Cao *et al.* (1997) found 15 genes differentially expressed in colorectal cancer compared to normal mucosal epithelium. Fitzpatrick *et al.* (1995) isolated 17 genes upregulated in rat liver following treatment with the peroxisome proliferator, clofibrate; Philips *et al.* (1990) isolated 12 cDNA clones which were upregulated in highly metastatic mammary adenocarcinoma cell lines compared to poorly metastatic ones. Prashar and Weissman (1996) used 3' restriction fragment analysis and identified approximately 40 genes showing altered expression within 4 h of activation of Jurkat T-cells. Groenink and Leegwater (1996) analysed 27 gene fragments isolated using SSH of delayed early response phase of liver regeneration and found only 12 to be upregulated.

In the laboratory, SSH was used to isolate up to 70 candidate genes which appear to show altered expression in guinea pig liver following short-term treatment with the peroxisome proliferator, WY-14,643 (Rockett, Swales, Esdaile and Gibson, unpublished observations). However, these findings have still to be confirmed by analysis of the extracted tissue mRNA for differential expression of these sequences.

Whilst the latest differential display technologies are purported to include design and experimental modifications to overcome this lack of efficiency (in both the total number of differentially expressed genes recovered and the percentage that are true



positives), it is still not clear if such adaptations are practically effective—proving efficiency by spiking with a known amount of limited numbers of artificial construct(s) is one thing, but isolating a high percentage of the rare messages already present in an mRNA population is another. Of course, some models will genuinely produce only a small number of differentially expressed genes. In addition, there are also technical problems that can reduce efficiency. For example, mRNAs may have an unusual primary structure that effectively prevents their amplification by PCR-based systems. In addition, it is known that under certain circumstances not all mRNAs have 3' polyA sites. For example, during *Xenopus* development, deadenylation is used as a means to stabilize RNAs (Voeltz and Steitz 1998), whilst preferential deadenylation may play a role in regulating Hsp70 (and perhaps, therefore, other stress protein) expression in *Drosophila* (Dellavalle *et al.* 1994). The presence of deadenylated mRNAs would clearly reduce the efficiency of systems utilizing a polydT reverse transcription step. The efficiency of any system also depends on the quality of the starting material. All differential display techniques use mRNA as their target material. However, it is difficult to isolate mRNA that is completely free of ribosomal RNA. Even if polydT primers are used to prime first strand cDNA synthesis, ribosomal RNA is often transcribed to some degree (Clontech PCR-Select cDNA Subtraction kit user manual). It has been shown, at least in the case of SSH, that a high rRNA:mRNA ratio can lead to inefficient subtractive hybridization (Clontech PCR-Select cDNA Subtraction kit user manual), and there is no reason to suppose that it will not do likewise in other SH approaches. Finally, those techniques that utilise a presubtraction amplification step (e.g. RDA) may present a skewed representation since some sequences amplify better than others.

Of course, probably the most important consideration is the temporal factor. It is clear that any given differential display experiment can only interrogate a cell at one point in time. It may well be that a high percentage of the genes showing altered expression at that time are obtained. However, given that disease processes and responses to environmental stimuli involve dynamic cascades of signalling, regulation, production and action, it is clear that all those genes which are switched on/off at different times will not be recovered and, therefore, vital information may well be missed. It is, therefore, imperative to obtain as much information about the model system beforehand as possible, from which a strategy can be derived for targeting specific time points or events that are of particular interest to the investigator. One way of getting round this problem of single time point analysis is to conduct the experiment over a suitable time course which, of course, adds substantially to the amount of work involved.

#### *How sensitive are differential expression technologies?*

There has been little published data that addresses the issue of how large the change in expression must be for it to permit isolation of the gene in question with the various differential expression technologies. Although the isolation of genes whose expression is changed as little as 1.5-fold has been reported using SSH (Groenink and Leegwater 1996), it appears that those demonstrating a change in excess of 5-fold are more likely to be picked up. Thus, there is a 'grey zone' in between where small changes could fade in and out of isolation between

experiments and animals. DD, on the other hand, is not subject to this grey zone since, unlike SH approaches, it does not amplify the difference in expression between two samples. Wan *et al.* (1996) reported that differences in expression of twofold or more are detectable using DD.

#### *Resolution and visualization of differential expression products*

It seems highly improbable with current technology that a gel system could be developed that is able to resolve all gene species showing altered expression in any given test system (be it SH- or DD-based). Polyacrylamide gel electrophoresis (PAGE) can resolve size differences down to 0.2% (Sambrook *et al.* 1989) and are used as standard in DD experiments. Even so, it is clear that a complex series of gene products such as those seen in a DD will contain unresolvable components. Thus, what appears to be one band in a gel may in fact turn out to be several. Indeed, it has been well documented (Mathieu-Daude *et al.* 1996, Smith *et al.* 1997) that a single band extracted from a DD often represents a composite of heterogeneous products, and the same has been found for SSH displays in this laboratory (Rockett *et al.* 1997). One possible solution was offered by Mathieu-Daude *et al.* (1996), who extracted and reamplified candidate bands from a DD display and used single strand conformation polymorphism (SSCP) analysis to confirm which components represented the truly differentially expressed product.

Many scientists often try to avoid the use of PAGE where possible because it is technically more demanding than agarose gel electrophoresis (AGE). Unfortunately, high resolution agarose gels such as Metaphor (FMC, Lichfield, UK) and AquaPor HR (National Diagnostics, Hesse, UK), whilst easier to prepare and manipulate than PAGE, can only separate DNA sequences which differ in size by around 1.5–2% (15–20 base pairs for a 1Kb fragment). Thus, SSH, RDA or other such products which differ in size by less than this amount are normally not resolvable. However, a simple technique does in fact exist for increasing the resolving power of AGE—the inclusion of HA-red (10-phenyl neutral red-PEG ligand) or HA-yellow (bisbenzamide-PEG ligand) (Hanse Analytik GmbH, Bremen, Germany) in a gel separates identical or closely sized products on base content. Specifically, HA-red and -yellow selectively bind to GC and AT DNA motifs, respectively (Wawer *et al.* 1995, Hanse Analytik 1997, personal communication). Since both HA-stains possess an overall positive charge, they migrate towards the cathode when an electric field is applied. This is in direct opposition to DNA, which is negatively charged and, therefore, migrates towards the anode. Thus, if two DNA clones are identical in size (as perceived on a standard high resolution agarose gel), but differ in AT/GC content, inclusion of a HA-dye in the gel will effectively retard the migration of one of the sequences compared to the other, effectively making it apparently larger and, thus, providing a means of differentiating between the two. The use of HA-red has been shown to resolve sequences with an AT variation of less than 1% (Wawer *et al.* 1995), whilst Hanse Analytik have reported that HA staining is so sensitive that in one case it was used to distinguish two 567bp sequences which differed by only a single point mutation (Hanse Analytik 1996, personal communication). Therefore, if one wishes to check whether all the clones produced from a specific band in a differential display experiment are derived from the same gene species, a small amount of reamplified or digested clone can be run on a standard high resolution gel, and a second aliquot

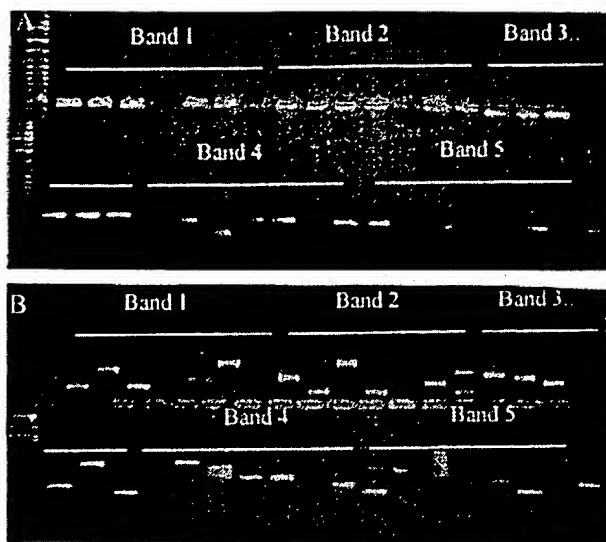


Figure 10. Discrimination of clones of identical/nearly identical size using HA-red. Bands of decreasing size (1–5) were extracted from the final display of a suppression subtractive hybridization experiment and cloned. Seven colonies were picked at random from each cloned band and their inserts amplified using PCR. The products were run on two gels, (A) a high resolution 2% agarose gel, and (B) a high resolution 2% agarose gel containing 1 U/ml HA-red. With few exceptions, all the clones from each band appear to be the same size (gel A). However, the presence of HA-red (gel B), which separates identically-sized DNA fragments based on the percentage of GC within the sequence, clearly indicates the presence of different gene species within each band. For example, even though all five re-amplified clones of band 1 appear to be the same size, at least four different gene species are represented.

in a similar gel containing one of the HA-stains. The standard gel should indicate any gross size differences, whilst the HA-stained gel should separate otherwise unresolvable species (on standard AGE) according to their base content. Geisinger *et al.* (1997) reported successful use of this approach for identifying DD-derived clones. Figure 10 shows such an experiment carried out in this laboratory on clones obtained from a band extracted from an SSH display.

An alternative approach is to carry out a 2-D analysis of the differential display products. In this approach, size-based separation is first carried out in a standard agarose gel. The gel slice containing the display is then extracted and incorporated in to a HA gel for resolution based on AT/GC content.

Of course, one should always consider the possibility of there being different gene species which are the same size and have the same GC/AT content. However, even these species are not unresolvable given some effort—again, one might use SSCP, or perhaps a denaturing gradient gel electrophoresis (DGGE) or temperature gradient field electrophoresis (TGGE) approach to resolve the contents of a band, either directly on the extracted band (Suzuki *et al.* 1991) or on the reamplified product.

The requirement of some differential display techniques to visualize large numbers of products (e.g. DD and GEF) can also present a problem in that, in terms of numbers, the resolution of PAGE rarely exceeds 300–400 bands. One approach to overcoming this might be to use 2-D gels such as those described by Uitterlinden *et al.* (1989) and Hatada *et al.* (1991).

Extraction of differentially expressed bands from a gel can be complex since, in some cases (e.g. DD, GEF), the results are visualized by autoradiographic means, such that precise overlay of the developed film on the gel must occur if the correct band is to be extracted for further analysis. Clearly, a misjudged extraction can account for many man-hours lost. This problem, and that of the use of radioisotopes, has been addressed by several groups. For example, Lohmann *et al.* (1995) demonstrated that silver staining can be used directly to visualize DD bands in horizontal PAGs. An *et al.* (1996) avoided the use of radioisotopes by transferring a small amount (20–30%) of the DNA from their DD to a nylon membrane, and visualizing the bands using chemiluminescent staining before going back to extract the remaining DNA from the gel. Chen and Peck (1996) went one step further and transferred the entire DD to a nylon membrane. The DNA bands were then visualized using a digoxigenin (DIG) system (DIG was attached to the polydT primers used in the differential display procedure). Differentially expressed bands were cut from the membrane and the DNA eluted by washing with PCR buffer prior to reamplification.

One of the advantages of using techniques such as SSH and RDA is that the final display can be run on an agarose gel and the bands visualized with simple ethidium bromide staining. Whilst this approach can provide acceptable results, over staining with SYBR Green I or SYBR Gold nucleic acid stains (FMC) effectively enhances the intensity and sharpness of the bands. This greatly aids in their precise extraction and often reveals some faint products that may otherwise be overlooked. Whilst differential displays stained with SYBR Green I are better visualized using short wavelength UV (254 nm) rather than medium wavelength (306 nm), the shorter wavelength is much more DNA damaging. In practice, it takes only a few seconds to damage DNA extracted under 254 nm irradiation, effectively preventing reamplification and cloning. The best approach is to over stain with SYBR Green I and extract bands under a medium wavelength UV transillumination.

#### **The possible use of 'microfingerprinting' to reduce complexity**

Given the sheer number of gene products and the possible complexity of each band, an alternative approach to rapid characterization may be to use an enhanced analysis of a small section of a differential display—a 'sub-fingerprint' or 'micro-fingerprint'. In this case, one could concentrate on those bands which only appear in a particular chosen size region. Reducing the fingerprint in this way has at least two advantages. One is that it should be possible to use different gel types, concentrations and run times tailored exactly to that region. Currently, one might run products from 100–3000 + bp on the same gel, which leads to compromise in the gel system being used and consequently to suboptimal resolution, both in terms of size and numbers, and can lead to problems in the accurate excision of individual bands. Secondly, it may be possible to enhance resolution by using a 2-D analysis using a HA-stain, as described earlier. In summary, if a range of gene product sizes is carefully chosen to include certain 'relevant' genes, the 2-D system standardized, and appropriate gene analysis used, it may be possible to develop a method for the early and rapid identification of compounds which have similar or widely different cellular effects. If the prognosis for exposure to one or more other chemicals which display a similar profile is already known, then one could perhaps predict similar effects for any new compounds which show a similar micro-fingerprint.

An alternative approach to microfingerprinting is to examine altered expression in specific families of genes through careful selection of PCR primers and/or post-reaction analysis. Stress genes, growth factors and/or their receptors, cell cycling genes, cytochromes P450 and regulatory proteins might be considered as candidates for analysis in this way. Indeed, some off-the-shelf DNA arrays (e.g. Clontech's Atlas cDNA Expression Array series) already anticipated this to some degree by grouping together genes involved in different responses e.g. apoptosis, stress, DNA-damage response etc.

## Screening

### *False positives*

The generation of false positives has been discussed at length amongst the differential display community (Liang *et al.* 1993, 1995, Nishio *et al.* 1994, Sun *et al.* 1994, Sompayrac *et al.* 1995). The reason for false positives varies with the technique being used. For instance, in RDA, the use of adaptors which have not been HPLC purified can lead to the production of false positives through illegitimate ligation events (O'Neill and Sinclair 1997), whilst in DD they can arise through PCR artifacts and illegitimate transcription of rRNA. In SH, false positives appear to be derived largely from abundant gene species, although some may arise from cDNA/mRNA species which do not undergo hybridization for technical reasons.

A quick screening of putative differentially expressed clones can be carried out using a simple dot blot approach, in which labelled first strand probes synthesized from tester and driver mRNA are hybridized to an array of said clones (Hedrick *et al.* 1984, Sakaguchi *et al.* 1986). Differentially expressed clones will hybridize to tester probe, but not driver. The disadvantage of this approach is that rare species may not generate detectable hybridization signals. One option for those using SSH is to screen the clones using a labelled probe generated from the subtracted cDNA from which it was derived, and with a probe made from the reverse subtraction reaction (ClonTechniques 1997a). Since the SSH method enriches rare sequences, it should be possible to confirm the presence of clones representing low abundance genes. Despite this quick screening step, there is still the need to go back to the original mRNA and confirm the altered expression using a more quantitative approach. Although this may be achieved using Northern blots, the sensitivity is poor by today's high standards and one must rely on PCR methods for accurate and sensitive determinations (see below).

## Sequence analysis

The majority of differential display procedures produce final products which are between 100 and 1000bp in size. However, this may considerably reduce the size of the sequence for analysis of the DNA databases. This in turn leads to a reduced confidence in the result—several families of genes have members whose DNA sequences are almost identical except in a few key stretches, e.g. the cytochrome P450 gene superfamily (Nelson *et al.* 1996). Thus, does the clone identified as being almost identical to gene  $X_0$  really come from that gene, or its brother gene  $X_1$ , or its as yet undiscovered sister  $X_2$ ? For example, using SSH, part of a gene was isolated,

which was up-regulated in the liver of rats exposed to Wy-14,643 and was identified by a FASTA search as being transferrin (data not shown). However, transferrin is known to be downregulated by hypolipidemic peroxisome proliferators such as Wy-14,643 (Hertz *et al.* 1996), and this was confirmed with subsequent RT-PCR analysis. This suggests that the gene sequence isolated may belong to a gene which is closely related to transferrin, but is regulated by a different mechanism.

A further problem associated with SH technology is redundancy. In most cases before SH is carried out, the cDNA population must first be simplified by restriction digestion. This is important for at least two reasons:

- (1) To reduce complexity—long cDNA fragments may form complex networks which prevent the formation of appropriate hybrids, especially at the high concentrations required for efficient hybridization.
- (2) Cutting the cDNAs into small fragments provides better representation of individual genes. This is because genes derived from related but distinct members of gene families often have similar coding sequences that may cross-hybridize and be eliminated during the subtraction procedure (Ko 1990). Furthermore, different fragments from the same cDNA may differ considerably in terms of hybridization and amplification and, thus, may not efficiently do one or the other (Wang and Brown 1991). Thus, some fragments from differentially expressed cDNAs may be eliminated during subtractive hybridization procedures. However, other fragments may be enriched and isolated. As a consequence of this, some genes will be cut one or more times, giving rise to two or more fragments of different sizes. If those same genes are differentially expressed, then two or more of the different size fragments may come through as separate bands on the final differential display, increasing the observed redundancy and increasing the number of redundant sequencing reactions.

Sequence comparisons also throw up another important point—at what degree of sequence similarity does one accept a result. Is 90% identity between a gene derived from your model species and another acceptably close? Is 95% between your sequence and one from the same species also acceptable? This problem is particularly relevant when the forward and reverse sequence comparisons give similar sequences with completely different gene species! An arbitrary decision seems to be to allocate genes that are definite (95% and above similarity) and then group those between 60 and 95% as being related or possible homologues.

### Quantitative analysis

At some point, one must give consideration to the quantitative analysis of the candidate genes, either as a means of confirming that they are truly differentially expressed, or in order to establish just what the differences are. Northern blot analysis is a popular approach as it is relatively easy and quick to perform. However, the major drawback with Northern blots is that they are often not sensitive enough to detect rare sequences. Since the majority of messages expressed in a cell are of low abundance (see table 1), this is a major problem. Consequently, RT-PCR may be the method of choice for confirming differential expression. Although the procedure is somewhat more complex than Northern analysis, requiring synthesis of primers and optimization of reaction conditions for each gene species, it is now possible to set up high throughput PCR systems using multichannel pipettes, 96 +well plates and

appropriate thermal cycling technology. Whilst quantitative analysis is more desirable, being more accurate and without reliance on an internal standard, the money and time needed to develop a competitor molecule is often excessive, especially when one might be examining tens or even hundreds of gene species. The use of semi-quantitative analysis is simpler, although still relatively involved. One must first of all choose an internal standard that does not change in the test cells compared to the controls. Numerous reference genes have been tried in the past, for example interferon-gamma (IFN- $\gamma$ , Frye *et al.* 1989),  $\beta$ -actin (Heuval *et al.* 1994), glyceraldehyde-3-phosphate dehydrogenase (GAPDH, Wong *et al.* 1994), dihydrofolate reductase (DHFR, Mohler and Butler 1991),  $\beta$ -2-microglobulin ( $\beta$ -2-m, Murphy *et al.* 1990), hypoxanthine phosphoribosyl transferase (HPRT, Foss *et al.* 1998) and a number of others (ClonTechniques 1997b). Ideally, an internal standard should not change its level of expression in the cell regardless of cell age, stage in the cell cycle or through the effects of external stimuli. However, it has been shown on numerous occasions that the levels of most housekeeping genes currently used by the research community do in fact change under certain conditions and in different tissues (ClonTechniques 1997b). It is imperative, therefore, that preliminary experiments be carried out on a panel of housekeeping genes to establish their suitability for use in the model system.

Interpretation of quantitative data must also be treated with caution. By comparing the lists of genes identified by differential expression one can perhaps gain insight into why two different species react in different ways to external stimuli. For example, rats and mice appear sensitive to the non-genotoxic effects of a wide range of peroxisome proliferators whilst Syrian hamsters and guinea pigs are largely resistant (Orton *et al.* 1984, Rodricks and Turnbull 1987, Lake *et al.* 1989, 1993, Makowska *et al.* 1992). A simplified approach to resolving the reason(s) why is to compare lists of up- and down-regulated genes in order to identify those which are expressed in only one species and, through background knowledge of the effects of the said gene, might suggest a mechanism of facilitated non-genotoxic carcinogenesis or protection. Of course, the situation is likely to be far more complex. Perhaps if there were one key gene protecting guinea pig from non-genotoxic effects and it was upregulated 50 times by PPs, the same gene might only be up-regulated five times in the rat. However, since both were noted to be upregulated, the importance of the gene may be overlooked. Just to complicate matters, a large change in expression does not necessarily mean a biologically important change. For example, what is the true relevance of gene Y which shows a 50-fold increase after a particular treatment, and gene Z which shows only a 5-fold increase? If one examines the literature one may find that historically, gene Y has often been shown to be up-regulated 40–60-fold by a number of unrelated stimuli—in light of this the 50-fold increase would appear less significant. However, the literature may show that gene Z has never been recorded as having more than doubled in expression—which makes your 5-fold increase all the more exciting. Perhaps even more interesting is if that same 5-fold increase has only been seen in related neoplasms or following treatment with related chemicals.

#### **Problems in using the differential display approach**

Differential display technology originally held promise of an easily obtainable 'fingerprint' of those genes which are up- or down-regulated in test animals/cells in a developmental process or following exposure to given stimuli. However, it has

become clear that the fingerprinting process, whilst still valid, is much too complex to be represented by a single technique profile. This is because all differential display techniques have common and/or unique technical problems which preclude the isolation and identification of all those genes which show changes in expression. Furthermore, there are important genetic changes related to disease development which differential expression analysis is simply not designed to address. An example of this is the presence of small deletions, insertions, or point mutations such as those seen in activated oncogenes, tumour suppressor genes and individual polymorphisms. Polymorphic variations, small though they usually are, are often regarded as being of paramount importance in explaining why some patients respond better than others to certain drug treatments (and, in logical extension, why some people are less affected by potentially dangerous xenobiotics/carcinogens than others). The identification of such point mutations and naturally occurring polymorphisms requires the subsequent application of sequencing, SSCP, DGGE or TGGE to the gene of interest. Furthermore, differential display is not designed to address issues such as alternatively spliced gene species or whether an increased abundance of mRNA is a result of increased transcription or increased mRNA stability.

### *Conclusions*

Perhaps the main advantage of open system differential display techniques is that they are not limited by extant theories or researcher bias in revealing genes which are differentially expressed, since they are designed to amplify all genes which demonstrate altered expression. This means that they are useful for the isolation of previously unknown genes which may turn out to be useful biomarkers of a particular state or condition. At least one open system (SAGE) is also quantitative, thus eliminating the need to return to the original mRNA and carry out Northern/PCR analysis to confirm the result. However, the rapid progress of genome mapping projects means that over the next 5–10 years or so, the balance of experimental use will switch from open to closed differential display systems, particularly DNA arrays. Arrays are easier and faster to prepare and use, provide quantitative data, are suitable for high throughput analysis and can be tailored to look at specific signalling pathways or families of genes. Identification of all the gene sequences in human and common laboratory animals combined with improved DNA array technology, means that it will soon no longer be necessary to try to isolate differentially expressed genes using the technically more demanding open system approach. Thus, their main advantage (that of identifying unknown genes) will be largely eradicated. It is likely, therefore, that their sphere of application will be reduced to analysis of the less common laboratory species, since it will be some time yet before the genomes of such animals as zebrafish, electric eels, gerbils, crayfish and squid, for example, will be sequenced.

Of course, in the end the question will always remain: What is the functional/biological significance of the identified, differentially expressed genes? One persistent problem is understanding whether differentially expressed genes are a cause or consequence of the altered state. Furthermore, many chemicals, such as non-genotoxic carcinogens, are also mitogens and so genes associated with replication will also be upregulated but may have little or nothing to do with the



carcinogenic effect. Whilst differential display technology cannot hope to answer these questions, it does provide a springboard from which identification, regulatory and functional studies can be launched. Understanding the molecular mechanism of cellular responses is almost impossible without knowing the regulation and function of those genes and their condition (e.g. mutated). In an abstract sense, differential display can be likened to a still photograph, showing details of a fixed moment in time. Consider the Historian who knows the outcome of a battle and the placement and condition of the troops before the battle commenced, but is asked to try and deduce how the battle progressed and why it ended as it did from a few still photographs—an impossible task. In order to understand the battle, the Historian must find out the capabilities and motivation of the soldiers and their commanding officers, what the orders were and whether they were obeyed. He must examine the terrain, the remains of the battle and consider the effects the prevailing weather conditions exerted. Likewise, if mechanistic answers are to be forthcoming, the scientist must use differential display in combination with other techniques, such as knockout technology, the analysis of cell signalling pathways, mutation analysis and time and dose response analyses. Although this review has emphasized the importance of differential gene profiling, it should not be considered in isolation and the full impact of this approach will be strengthened if used in combination with functional genomics and proteomics (2-dimensional protein gels from isoelectric focusing and subsequent SDS electrophoresis and virtual 2D-maps using capillary electrophoresis). Proteomics is attracting much recent attention as many of the changes resulting in differential gene expression do not involve changes in mRNA levels, as described extensively herein, but rather protein-protein, protein-DNA and protein phosphorylation events which would require functional genomics or proteomic technologies for investigation.

Despite the limitations of differential display technology, it is clear that many potential applications and benefits can be obtained from characterizing the genetic changes that occur in a cell during normal and disease development and in response to chemical or biological insult. In light of functional data, such profiling will provide a 'fingerprint' of each stage of development or response, and in the long term should help in the elucidation of specific and sensitive biomarkers for different types of chemical/biological exposure and disease states. The potential medical and therapeutic benefits of understanding such molecular changes are almost immeasurable. Amongst other things, such fingerprints could indicate the family or even specific type of chemical an individual has been exposed to plus the length and/or acuteness of that exposure, thus indicating the most prudent treatment. They may also help uncover differences in histologically identical cancers, provide diagnostic tests for the earliest stages of neoplasia and, again, perhaps indicate the most efficacious treatment.

The Human Genome Project will be completed early in the next century and the DNA sequence of all the human genes will be known. The continuing development and evolution of differential gene expression technology will ensure that this knowledge contributes fully to the understanding of human disease processes.

#### **Acknowledgements**

We acknowledge Drs Nick Plant (University of Surrey), Sally Darney and Chris Luft (US EPA at RTP) for their critical analysis of the manuscript prior to submission. This manuscript has been reviewed in accordance with the policy of the

US Environmental Protection Agency and approved for publication. Approval does not signify that the contents reflect the views and policies of the Agency, nor does mention of trade names constitute endorsement or recommendation for use.

## References

- ADAMS, M. D., KELLEY, J. M., GOCAYNE, J. D., DUBNICK, M., POLYMERPOULOS, M. H., XIAO, H., MERRILL, C. R., WU, A., OLDE, B., MORENO, R. F., KERLAVAGE, A. R., MCCOMBIE, W. R. and VENTOR, J. C., 1991, Complementary DNA sequencing: expressed sequence tags and human genome project. *Science*, **252**, 1651-1656.
- AN, G., LUO, G., VELTRI, R. W. and O'HARA, S. M., 1996, Sensitive non-radioactive differential display method using chemiluminescent detection. *Biotechniques*, **20**, 342-346.
- AXEL, R., FEIGELSON, P. and SCHULTZ, G., 1976, Analysis of the complexity and diversity of mRNA from chicken liver and oviduct. *Cell*, **7**, 247-254.
- BAND, V. and SAGER, R., 1989, Distinctive traits of normal and tumor-derived human mammary epithelial cells expressed in a medium that supports long-term growth of both cell types. *Proceedings of the National Academy of Sciences, USA*, **86**, 1249-1253.
- BAUER, D., MULLER, H., REICH, J., RIEDEL, H., AHRENKIEL, V., WARTHOF, P. and STRAUSS, M., 1993, Identification of differentially expressed mRNA species by an improved display technique (DDRT-PCR). *Nucleic Acids Research*, **21**, 4272-4280.
- BERTIOLI, D. J., SCHLICHTER, U. H. A., ADAMS, M. J., BURROWS, P. R., STEINBISS, H.-H. and ANTONIW, J. F., 1995, An analysis of differential display shows a strong bias towards high copy number mRNAs. *Nucleic Acids Research*, **23**, 4520-4523.
- BRAVO, R., 1990, Genes induced during the G0/G1 transition in mouse fibroblasts. *Seminars in Cancer Biology*, **1**, 37-46.
- BURN, T. C., PETROVICK, M. S., HOHAUS, S., ROLLINS, B. J. and TENEN, D. G., 1994, Monocyte chemoattractant protein-1 gene is expressed in activated neutrophils and retinoic acid-induced human myeloid cell lines. *Blood*, **84**, 2776-2783.
- CAO, J., CAI, X., ZHENG, L., GENG, L., SHI, Z., PAO, C. C. and ZHENG, S., 1997, Characterisation of colorectal cancer-related cDNA clones obtained by subtractive hybridisation screening. *Journal of Cancer Research and Clinical Oncology*, **123**, 447-451.
- CASSIDY, S. B., 1995, Uniparental disomy and genomic imprinting as causes of human genetic disease. *Environmental and Molecular Mutagenesis*, **25** (Suppl 26), 13-20.
- CHANG, G. W. and TERZAGHI-HOWE, M., 1998, Multiple changes in gene expression are associated with normal cell-induced modulation of the neoplastic phenotype. *Cancer Research*, **58**, 4445-4452.
- CHEN, J., SCHWARTZ, D. A., YOUNG, T. A., NORRIS, J. S. and YAGER, J. D., 1996, Identification of genes whose expression is altered during mitosis suppression in livers of ethinyl estradiol-treated female rats. *Carcinogenesis*, **17**, 2783-2786.
- CHEN, J. J. W. and PECK, K., 1996, Non-radioactive differential display method to directly visualise and amplify differential bands on nylon membrane. *Nucleic Acid Research*, **24**, 793-794.
- CLON TECHNIQUES, 1997a, PCR-Select Differential Screening Kit—the next step after Clontech PCR-Select cDNA subtraction. *ClonTechniques*, **XII**, 18-19.
- CLON TECHNIQUES, 1997b, Housekeeping RT-PCR amplimers and cDNA probes. *ClonTechniques*, **XII**, 15-16.
- DAVIS, M. M., COHEN, D. I., NIELSEN, E. A., STEINMETZ, M., PAUL, W. E. and HOOD, L., 1984, Cell-type-specific cDNA probes and the murine I region: the localization and orientation of Ad alpha. *Proceedings of the National Academy of Sciences (USA)*, **81**, 2194-2198.
- DELLAVALLE, R. P., PETERSON, R. and LINDQUIST, S., 1994, Preferential deadenylation of HSP70 mRNA plays a key role in regulating Hsp70 expression in *Drosophila melanogaster*. *Molecular and Cell Biology*, **14**, 3646-3659.
- DERISI, J. L., VASHWANATH, R. L. and BROWN, P., 1997, Exploring the metabolic and genetic control of gene expression on a genomic scale. *Science*, **278**, 680-686.
- DIATCHENKO, L., LAU, Y.-F. C., CAMPBELL, A. P., CHENCHIK, A., MOQADAM, F., HUANG, B., LUKYANOV, K., GURSKAYA, N., SVERDLOV, E. D. and SIEBERT, P. D., 1996, Suppression subtractive hybridisation: A method for generating differentially regulated or tissue-specific cDNA probes and libraries. *Proceedings of the National Academy of Sciences (USA)*, **93**, 6025-6030.
- DOGRA, S. C., WHITELAW, M. L. and MAY, B. K., 1998, Transcriptional activation of cytochrome P450 genes by different classes of chemical inducers. *Clinical and Experimental Pharmacology and Physiology*, **25**, 1-9.
- DUGUID, J. R. and DINAUER, M. C., 1990, Library subtraction of *in vitro* cDNA libraries to identify differentially expressed genes in scrapie infection. *Nucleic Acids Research*, **18**, 2789-2792.
- DUNBAR, P. R., OGG, G. S., CHEN, J., RUST, N., VAN DER BRUGGEN, P. and CERUNDOLO, V., 1998, Direct isolation, phenotyping and cloning of low-frequency antigen-specific cytotoxic T lymphocytes from peripheral blood. *Current Biology*, **26**, 413-416.

- FITZPATRICK, D. R., GERMAIN -LEE, E. and VALLE, D., 1995, Isolation and characterisation of rat and human cDNAs encoding a novel putative peroxisomal enoyl-CoA hydratase. *Genomics*, **27**, 457-466.
- FOSS, D. L., BAARSCH, M. J. and MURTAUGH, M. P., 1998, Regulation of hypoxanthine phosphoribosyltransferase, glyceraldehyde-3-phosphate dehydrogenase and beta-actin mRNA expression in porcine immune cells and tissues. *Animal Biotechnology*, **9**, 67-78.
- FRYE, R. A., BENZ, C. C. and LIU, E., 1989, Detection of amplified oncogenes by differential polymerase chain reaction. *Oncogene*, **4**, 1153-1157.
- GEISINGER, A., RODRIGUEZ, R., ROMERO, V. and WETTSTEIN, R., 1997, A simple method for screening cDNAs arising from the cloning of RNA differential display bands. *Elsevier Trends Journals Technical Tips Online*, <http://tto.trends.com>, document T01110.
- GRESS, T. M., HOHEISEL, J. D., LENNON, G. G., ZEHETNER, G. and LEHRACH, H., 1992, Hybridisation fingerprinting of high density cDNA filter arrays with cDNA pools derived from whole tissues. *Mammalian Genome*, **3**, 609-619.
- GRIFFIN, G. and KRISHNA, S., 1998, Cytokines in infectious diseases. *Journal of the Royal College of Physicians, London*, **32**, 195-198.
- GROENINK, M. and LEEGWATER, A. C. J., 1996, Isolation of delayed early genes associated with liver regeneration using Clontech PCR-select subtraction technique. *Clontechniques*, **XI**, 23-24.
- GUIMARAES, M. J., BAZAN, J. F., ZLOTNIK, A., WILES, M. V., GRIMALDI, J. C., LEE, F. and McCLANAHAN, T., 1995b, A new approach to the study of haematopoietic development in the yolk sac and embryoid bodies. *Development*, **121**, 3335-3346.
- GUIMARAES, M. J., LEE, F., ZLOTNIK, A. and McCLANAHAN, T., 1995a, Differential display by PCR: novel findings and applications. *Nucleic Acids Research*, **23**, 1832-1833.
- GURSKAYA, N. G., DIATCHENKO, L., CHENCHIK, P. D., SIEBERT, P. D., KHASPEKOV, G. L., LUKYANOV, K. A., VAGNER, L. L., ERMOLAEVA, O. D., LUKYANOV, S. A. and SVERDLOV, E. D., 1996, Equalising cDNA subtraction based on selective suppression of polymerase chain reaction: Cloning of Jurkat cell transcripts induced by phytohemagglutinin and phorbol 12-Myristate 13-Acetate. *Analytical Biochemistry*, **240**, 90-97.
- HAMPSON, I. N. and HAMPSON, L., 1997, CCLS and DROP—subtractive cloning made easy. *Life Science News* (A publication of Amersham Life Science), **23**, 22-24.
- HAMPSON, I. N., HAMPSON, L. and DEXTER, T. M., 1996, Directional random oligonucleotide primed (DROP) global amplification of cDNA: its application to subtractive cDNA cloning. *Nucleic Acids Research*, **24**, 4832-4835.
- HAMPSON, I. N., POPE, L., COWLING, G. J. and DEXTER, T. M., 1992, Chemical cross linking subtraction (CCLS): a new method for the generation of subtractive hybridisation probes. *Nucleic Acids Research*, **20**, 2899.
- HARA, E., KATO, T., NAKADA, S., SEKIYA, S. and ODA, K., 1991, Subtractive cDNA cloning using oligo(dT)30-latex and PCR: isolation of cDNA clones specific to undifferentiated human embryonal carcinoma cells. *Nucleic Acids Research*, **19**, 7097-7104.
- HATADA, I., HAYASHIZAKE, Y., HIROTSUNE, S., KOMATSUBARA, H. and MUKAI, T., 1991, A genomic scanning method for higher organisms using restriction sites as landmarks. *Proceedings of the National Academy of Sciences (USA)*, **88**, 9523-9527.
- HECHT, N., 1998, Molecular mechanisms of male sperm cell differentiation. *Bioessays*, **20**, 555-561.
- HEDRICK, S., COHEN, D. I., NIELSEN, E. A. and DAVIS, M. E., 1984, Isolation of T cell-specific membrane-associated proteins. *Nature*, **308**, 149-153.
- HERTZ, R., SECKBACH, M., ZAKIN, M. M. and BAR-TANA, J., 1996, Transcriptional suppression of the transferrin gene by hypolipidemic peroxisome proliferators. *Journal of Biological Chemistry*, **271**, 218-224.
- HEUVAL, J. P. V., CLARK, G. C., KOHN, M. C., TRITSCHER, A. M., GREENLEE, W. F., LUCIER, G. W. and BELL, D. A., 1994, Dioxin-responsive genes: Examination of dose-response relationships using quantitative reverse transcriptase-polymerase chain reaction. *Cancer Research*, **54**, 62-68.
- HILLIER, L. D., LENNON, G., BECKER, M., BONALDO, M. F., CHIAPELLI, B., CHISSOE, S., DIETRICH, N., DUBUQUE, T., FAVELLO, A., GISH, W., HAWKINS, M., HULTMAN, M., KUCABA, T., LACY, M., LE, M., LE, N., MARDIS, E., MOORE, B., MORRIS, M., PARSONS, J., PRANGE, C., RIFKIN, L., ROHLFING, T., SCHELLENBERG, K., SOARES, M. B., TAN, F., THIERRY-MEG, J., TREVASKIS, E., UNDERWOOD, K., WOHLDMAN, P., WATERSTON, R., WILSON, R. and MARRA, M., 1996, Generation and analysis of 280,000 human expressed sequence tags. *Genome Research*, **6**, 807-828.
- HUBANK, M. and SCHATZ, D. G., 1994, Identifying differences in mRNA expression by representational difference analysis. *Nucleic Acids Research*, **22**, 5640-5648.
- HUNTER, T., 1991, Cooperation between oncogenes. *Cell*, **64**, 249-270.
- IVANOVA, N. B. and BELYAVSKY, A. V., 1995, Identification of differentially expressed genes by restriction endonuclease-based gene expression fingerprinting. *Nucleic Acids Research*, **23**, 2954-2958.
- JAMES, B. D. and HIGGINS, S. J., 1985, *Nucleic Acid Hybridisation* (Oxford: IRL Press Ltd).
- KAS-DEELEN, A. M., HARMSSEN, M. C., DE MAAR, E. F. and VAN SON, W. J., 1998, A sensitive method for

- quantifying cytomegalic endothelial cells in peripheral blood from cytomegalovirus-infected patients. *Clinical Diagnostic and Laboratory Immunology*, 5, 622-626.
- KILTY, I. and VICKERS, P., 1997, Fractionating DNA fragments generated by differential display PCR. *Strategies Newsletter (Stratagene)*, 10, 50-51.
- KLEINJAN, D.-J. and van HEYNINGEN, V., 1998, Position effect in human genetic disease. *Human and Molecular Genetics*, 7, 1611-1618.
- KO, M. S., 1990, An 'equalized cDNA library' by the reassociation of short double-stranded cDNAs. *Nucleic Acids Research*, 18, 5705-5711.
- LAKE, B. G., EVANS, J. G., CUNNINGHAME, M. E. and PRICE, R. J., 1993, Comparison of the hepatic effects of Wy-14,643 on peroxisome proliferation and cell replication in the rat and Syrian hamster. *Environmental Health Perspectives*, 101, 241-248.
- LAKE, B. G., EVANS, J. G., GRAY, T. J. B., KOROSI, S. A. and NORTH, C. J., 1989, Comparative studies of nafenopin-induced hepatic peroxisome proliferation in the rat, Syrian hamster, guinea pig and marmoset. *Toxicology and Applied Pharmacology*, 99, 148-160.
- LENNARD, M. S., 1993, Genetically determined adverse drug reactions involving metabolism. *Drug Safety*, 9, 60-77.
- LEVY, S., TODD, S. C. and MAECKER, H. T., 1998, CD81(TAPA-1): a molecule involved in signal transduction and cell adhesion in the immune system. *Annual Review of Immunology*, 16, 89-109.
- LIANG, P. and PARDEE, A. B., 1992, Differential display of eukaryotic messenger RNA by means of the polymerase chain reaction. *Science*, 257, 967-971.
- LIANG, P., AVERBOUKH, L., KEYOMARSI, K., SAGER, R. and PARDEE, A., 1992, Differential display and cloning of messenger RNAs from human breast cancer versus mammary epithelial cells. *Cancer Research*, 52, 6966-6968.
- LIANG, P., AVERBOUKH, L. and PARDEE, A. B., 1993, Distribution & cloning of eukaryotic mRNAs by means of differential display refinements and optimisation. *Nucleic Acids Research*, 21, 3269-3275.
- LIANG, P., BAUER, D., AVERBOUKH, L., WARTHOF, P., ROHRWILD, M., MULLER, H., STRAUSS, M. and PARDEE, A. B., 1995, Analysis of altered gene expression by differential display. *Methods in Enzymology*, 254, 304-321.
- LINSKENS, M. H., FENG, J., ANDREWS, W. H., ENLOW, B. E., SAATI, S. M., TONKIN, L. A., FUNK, W. D. and VILLEPONTEAU, B., 1995, Cataloging altered gene expression in young and senescent cells using enhanced differential display. *Nucleic Acids Research*, 23, 3244-3251.
- LISITSYN, N., LISITSYN, N. and WIGLER, M., 1993, Cloning the differences between two complex genomes. *Science*, 259, 946-951.
- LOHMANN, J., SCHICKLE, H. and BOSCH, T. C. G., 1995, REN Display, a rapid and efficient method for non-radioactive differential display and mRNA isolation. *Biotechniques*, 18, 200-202.
- LUNNEY, J. K., 1998, Cytokines orchestrating the immune response. *Reviews in Science and Technology*, 17, 84-94.
- MAKOWSKA, J. M., GIBSON, G. G. and BONNER, F. W., 1992, Species differences in ciprofibrate-induction of hepatic cytochrome P450A1 and peroxisome proliferation. *Journal of Biochemical Toxicology*, 7, 183-191.
- MALDARELLI, F., XIANG, C., CHAMOUN, G. and ZEICHNER, S. L., 1998, The expression of the essential nuclear splicing factor SC35 is altered by human immunodeficiency virus infection. *Virus Research*, 53, 39-51.
- MATHIEU-DAUDE, F., CHENG, R., WELSH, J. and MCCLELLAND, M., 1996, Screening of differentially amplified cDNA products from RNA arbitrarily primed PCR fingerprints using single strand conformation polymorphism (SSCP) gels. *Nucleic Acids Research*, 24, 1504-1507.
- McKENZIE, D. and DRAKE, D., 1997, Identification of differentially expressed gene products with the castaway system. *Strategies Newsletter (Stratagene)*, 10, 19-20.
- MCCLELLAND, M., MATHIEU-DAUDE, F. and WELSH, J., 1996, RNA fingerprinting and differential display using arbitrarily primed PCR. *Trends in Genetics*, 11, 242-246.
- MECHLER, B. and RABBITTS, T. H., 1981, Membrane-bound ribosomes of myeloma cells. IV. mRNA complexity of free and membrane-bound polysomes. *Journal of Cell Biology*, 88, 29-36.
- MEYER, U. A. and ZANGER, U. M., 1997, Molecular mechanisms of genetic polymorphisms of drug metabolism. *Annual Review of Pharmacology and Toxicology*, 37, 269-296.
- MOHLER, K. M. and BUTLER, L. D., 1991, Quantitation of cytokine mRNA levels utilizing the reverse transcriptase-polymerase chain reaction following primary antigen-specific sensitization in vivo—I. Verification of linearity, reproducibility and specificity. *Molecular Immunology*, 28, 437-447.
- MURPHY, L. D., HERZOG, C. E., RUDICK, J. B., TITO FOJO, A. and BATES, S. E., 1990, Use of the polymerase chain reaction in the quantitation of the *mdr-1* gene expression. *Biochemistry*, 29, 10351-10356.
- NELSON, D. R., KOYMANS, L., KAMATAKI, T., STEGEMAN, J. J., FEYEREISEN, R., WAXMAN, D. J., WATERMAN, M. R., GOTOH, O., COON, M. J., ESTABROOK, R. W., GUNSALUS, I. C. and NEBERT, D. W., 1996, Update on new sequences, gene mapping, accession numbers and nomenclature. *Pharmacogenetics*, 6, 1-42.

- NISHIO, Y., AIELLO, L. P. and KING, G. L., 1994, Glucose induced genes in bovine aortic smooth muscle cells identified by mRNA differential display. *FASEB Journal*, **8**, 103-106.
- O'NEILL, M. J. and SINCLAIR, A. H., 1997, Isolation of rare transcripts by representational difference analysis. *Nucleic Acids Research*, **25**, 2681-2682.
- ORTON, T. C., ADAM, H. K., BENTLEY, M., HOLLOWAY, B. and TUCKER, M. J., 1984, Clobuzarit: species differences in the morphological and biochemical response of the liver following chronic administration. *Toxicology and Applied Pharmacology*, **73**, 138-151.
- PELKONEN, O., MAENPAA, J., TAAVITSAINEN, P., RAUTIO, A. and RAUNIO, H., 1998, Inhibition and Induction of human cytochrome P450 (CYP) enzymes. *Xenobiotica*, **28**, 1203-1253.
- PHILIPS, S. M., BENDALL, A. J. and RAMSHAW, I. A., 1990, Isolation of genes associated with high metastatic potential in rat mammary adenocarcinomas. *Journal of the National Cancer Institute*, **82**, 199-203.
- PRASHAR, Y. and WEISSMAN, S. M., 1996, Analysis of differential gene expression by display of 3' end restriction fragments of cDNAs. *Proceedings of the National Academy of Sciences (USA)*, **93**, 659-663.
- RAGNO, S., ESTRADA, I., BUTLER, R. and COLSTON, M. J., 1997, Regulation of macrophage gene expression following invasion by *Mycobacterium tuberculosis*. *Immunology Letters*, **57**, 143-146.
- RAMANA, K. V. and KOHLI, K. K., 1998, Gene regulation of cytochrome P450—an overview. *Indian Journal of Experimental Biology*, **36**, 437-446.
- RICHARD, L., VELASCO, P. and DETMAR, M., 1998, A simple immunomagnetic protocol for the selective isolation and long-term culture of human dermal microvascular endothelial cells. *Experimental Cell Research*, **240**, 1-6.
- ROCKETT, J. C., ESDAILE, D. J. and GIBSON, G. G., 1997, Molecular profiling of non-genotoxic hepatocarcinogenesis using differential display reverse transcription-polymerase chain reaction (ddRT-PCR). *European Journal of Drug Metabolism and Pharmacokinetics*, **22**, 329-333.
- RODRICKS, J. V. and TURNBULL, D., 1987, Inter-species differences in peroxisomes and peroxisome proliferation. *Toxicology and Industrial Health*, **3**, 197-212.
- ROGLER, G., HAUSMANN, M., VOGL, D., ASCHENBRENNER, E., ANDUS, T., FALK, W., ANDRESEN, R., SCHOLMERICH, J. and GROSS, V., 1998, Isolation and phenotypic characterization of colonic macrophages. *Clinical and Experimental Immunology*, **112**, 205-215.
- ROHN, W. M., LEE, Y. J. and BENVENISTE, E. N., 1996, Regulation of class II MHC expression. *Critical Reviews in Immunology*, **16**, 311-330.
- RUDIN, C. M. and THOMPSON, C. B., 1998, B-cell development and maturation. *Seminars in Oncology*, **25**, 435-446.
- SAKAGUCHI, N., BERGER, C. N. and MELCHERS, F., 1986, Isolation of a cDNA copy of an RNA species expressed in murine pre-B cells. *EMBO Journal*, **5**, 2139-2147.
- SAMBROOK, J., FRITSCH, E. F. and MANIATIS, T., 1989, Gel electrophoresis of DNA. In N. Ford, M. Nolan and M. Ferguson (eds), *Molecular Cloning—A laboratory manual*, 2nd edition (New York: Cold Spring Harbour Laboratory Press), Volume 1, pp. 6-37.
- SARGENT, T. D. and DAWID, I. B., 1983, Differential gene expression in the gastrula of *Xenopus laevis*. *Science*, **222**, 135-139.
- SCHENA, M., SHALON, D., HELLER, R., CHAI, A., BROWN, P. O. and DAVIS, R. W., 1996, Parallel human genome analysis: Microarray-based expression monitoring of 1000 genes. *Proceedings of the National Academy of Sciences (USA)*, **93**, 10614-10619.
- SCHNEIDER, C., KING, R. M. and PHILIPSON, L., 1988, Genes specifically expressed at growth arrest of mammalian cells. *Cell*, **54**, 787-793.
- SCHNEIDER-MAUNOURY, S., GILARDI-HEBENSTREIT, P. and CHARNAY, P., 1998, How to build a vertebrate hindbrain. Lessons from genetics. *C R Academy of Science III*, **321**, 819-834.
- SEMENTA, G. L., 1994, Transcriptional regulation of gene expression: mechanisms and pathophysiology. *Human Mutations*, **3**, 180-199.
- SEWALL, C. H., BELL, D. A., CLARK, G. C., TRITSCHER, A. M., TULLY, D. B., VANDEN HEUVEL, J. and LUCIER, G. W., 1995, Induced gene transcription: implications for biomarkers. *Clinical Chemistry*, **41**, 1829-1834.
- SINGH, N., AGRAWAL, S. and RASTOGI, A. K., 1997, Infectious diseases and immunity: special reference to major histocompatibility complex. *Emerging Infectious Diseases*, **3**, 41-49.
- SMITH, N. R., LI, A., ALDERSLEY, M., HIGH, A. S., MARKHAM, A. F. and ROBINSON, P. A., 1997, Rapid determination of the complexity of cDNA bands extracted from DDRT-PCR polyacrylamide gels. *Nucleic Acids Research*, **25**, 3552-3554.
- SOMPAYRAC, L., JANE, S., BURN, T. C., TENEN, D. G. and DANNA, K. J., 1995, Overcoming limitations of the mRNA differential display technique. *Nucleic Acids Research*, **23**, 4738-4739.
- ST JOHN, T. P. and DAVIS, R. W., 1979, Isolation of galactose-inducible DNA sequences from *Saccharomyces cerevisiae* by differential plaque filter hybridisation. *Cell*, **16**, 443-452.
- SUN, Y., HEGAMYER, G. and COLBURN, N. H., 1994, Molecular cloning of five messenger RNAs differentially expressed in preneoplastic or neoplastic JB6 mouse epidermal cells: one is homologous to human tissue inhibitor of metalloproteinases-3. *Cancer Research*, **54**, 1139-1144.

- SUNG, Y. J. and DENMAN, R. B., 1997, Use of two reverse transcriptases eliminates false-positive results in differential display. *Biotechniques*, **23**, 462-464.
- SUTTON, G., WHITE, O., ADAMS, M. and KERLAVAGE, A., 1995, TIGR Assembler; A new tool for assembling large shotgun sequencing projects. *Genome Science and Technology*, **1**, 9-19.
- SUZUKI, Y., SEKIYA, T. and HAYASHI, K., 1991, Allele-specific polymerase chain reaction: a method for amplification and sequence determination of a single component among a mixture of sequence variants. *Analytical Biochemistry*, **192**, 82-84.
- SYED, V., GU, W. and HECHT, N. B., 1997, Sertoli cells in culture and mRNA differential display provide a sensitive early warning assay system to detect changes induced by xenobiotics. *Journal of Andrology*, **18**, 264-273.
- UITERLINDEN, A. G., SLAGBOOM, P., KNOOK, D. L. and VIJGL, J., 1989, Two-dimensional DNA fingerprinting of human individuals. *Proceedings of the National Academy of Sciences (USA)*, **86**, 2742-2746.
- ULLMAN, K. S., NORTHROP, J. P., VERWEIJ, C. L. and CRABTREE, G. R., 1990, Transmission of signals from the T lymphocyte antigen receptor to the genes responsible for cell proliferation and immune function: the missing link. *Annual Review of Immunology*, **8**, 421-452.
- VASMATZIS, G., ESSAND, M., BRINKMANN, U., LEE, B. and PASTON, I., 1998, Discovery of three genes specifically expressed in human prostate by expressed sequence tag database analysis. *Proceedings of the National Academy of Sciences (USA)*, **95**, 300-304.
- VELCULESCU, V. E., ZHANG, L., VOGELSTEIN, B. and KINZLER, K. W., 1995, Serial analysis of gene expression. *Science*, **270**, 484-487.
- VOELTZ, G. K. and STEITZ, J. A., 1998, Auaa sequences direct mRNA deadenylation uncoupled from decay during *Xenopus* early development. *Molecular and Cell Biology*, **18**, 7537-7545.
- VOGELSTEIN, B. and KINZLER, K. W., 1993, The multistep nature of cancer. *Trends in Genetics*, **9**, 138-141.
- WALTER, J., BELFIELD, M., HAMPSON, I. and READ, C., 1997, A novel approach for generating subtractive probes for differential screening by CCLS. *Life Science News*, **21**, 13-14.
- WAN, J. S., SHARP, S. J., POIRIER, G. M.-C., WAGAMAN, P. C., CHAMBERS, J., PYATI, J., HOM, Y.-L., GALINDO, J. E., HUVAR, A., PETERSON, P. A., JACKSON, M. R. and ERLANDER, M. G., 1996, Cloning differentially expressed mRNAs. *Nature Biotechnology*, **14**, 1685-1691.
- WALTER, J., BELFIELD, M., HAMPSON, I. and READ, C., 1997, A novel approach for generating subtractive probes for differential screening by CCLS. *Life Science News*, **21**, 13-14.
- WANG, Z. and BROWN, D. D., 1991, A gene expression screen. *Proceedings of the National Academy of Sciences (USA)*, **88**, 11505-11509.
- WAWER, C., RUGGEBERG, H., MEYER, G. and MUYZER, G., 1995, A simple and rapid electrophoresis method to detect sequence variation in PCR-amplified DNA fragments. *Nucleic Acids Research*, **23**, 4928-4929.
- WELSH, J., CHADA, K., DALAL, S. S., CHENG, R., RALPH, D. and MCCLELLAND, M., 1992, Arbitrarily primed PCR fingerprinting of RNA. *Nucleic Acids Research*, **20**, 4965-4970.
- WONG, H., ANDERSON, W. D., CHENG, T. and RIABOWOL, K. T., 1994, Monitoring mRNA expression by polymerase chain reaction: the 'primer-dropping' method. *Analytical Biochemistry*, **223**, 251-258.
- WONG, K. K. and MCCLELLAND, M., 1994, Stress-inducible gene of *Salmonella typhimurium* identified by arbitrarily primed PCR of RNA. *Proceedings of the National Academy of Sciences (USA)*, **91**, 639-643.
- WYNFORD-THOMAS, D., 1991, Oncogenes and anti-oncogenes; the molecular basis of tumour behaviour. *Journal of Pathology*, **165**, 187-201.
- XHU, D., CHAN, W. L., LEUNG, B. P., HUANG, F. P., WHEELER, R., PIEDRAFITA, D., ROBINSON, J. H. and LIEW, F. Y., 1998, Selective expression of a stable cell surface molecule on type 2 but not type 1 helper T cells. *Journal of Experimental Medicine*, **187**, 787-794.
- YANG, M. and SYTOWSKI, A. J., 1996, Cloning differentially expressed genes by linker capture subtraction. *Analytical Biochemistry*, **237**, 109-114.
- ZHAO, N., HASHIDA, H., TAKAHASHI, N., MISUMI, Y. and SAKAKI, Y., 1995, High-density cDNA filter analysis: a novel approach for large scale quantitative analysis of gene expression. *Gene*, **156**, 207-213.
- ZHAO, X. J., NEWSOME, J. T. and CIHLAR, R. L., 1998, Up-regulation of two *Candida albicans* genes in the rat model of oral candidiasis detected by differential display. *Microbial Pathogenesis*, **25**, 121-129.
- ZIMMERMANN, C. R., ORR, W. C., LECLERC, R. F., BARNARD, C. and TIMBERLAKE, W. E., 1980, Molecular cloning and selection of genes regulated in *Aspergillus* development. *Cell*, **21**, 709-715.

## Whole genome analysis: Experimental access to all genome sequenced segments through larger-scale efficient oligonucleotide synthesis and PCR

DEVAL A. LASHKARI\*<sup>†</sup>, JOHN H. MCCUSKER<sup>‡</sup>, AND RONALD W. DAVIS\*<sup>§</sup>

\*Departments of Genetics and Biochemistry, Beckman Center, Stanford University, Stanford, CA 94305; and <sup>‡</sup>Department of Microbiology, 3020 Duke University Medical Center, Durham, NC 27710

Contributed by Ronald W. Davis, May 20, 1997

**ABSTRACT** The recent ability to sequence whole genomes allows ready access to all genetic material. The approaches outlined here allow automated analysis of sequence for the synthesis of optimal primers in an automated multiplex oligonucleotide synthesizer (AMOS). The efficiency is such that all ORFs for an organism can be amplified by PCR. The resulting amplicons can be used directly in the construction of DNA arrays or can be cloned for a large variety of functional analyses. These tools allow a replacement of single-gene analysis with a highly efficient whole-genome analysis.

The genome sequencing projects have generated and will continue to generate enormous amounts of sequence data. The genomes of *Saccharomyces cerevisiae*, *Escherichia coli*, *Haemophilus influenzae* (1), *Mycoplasma genitalium* (2), and *Methanococcus jannaschii* (3) have been completely sequenced. Other model organisms have had substantial portions of their genomes sequenced as well, including the nematode *Caenorhabditis elegans* (4) and the small flowering plant *Arabidopsis thaliana* (5). This massive and increasing amount of sequence information allows the development of novel experimental approaches to identify gene function.

One standard use of genome sequence data is to attempt to identify the functions of predicted open reading frames (ORFs) within the genome by comparison to genes of known function. Such a comparative analysis of all ORFs to existing sequence data is fast, simple, and requires no experimentation and is therefore a reasonable first step. While finding sequence homologies/motifs is not a substitute for experimentation, noting the presence of sequence homology and/or sequence motifs can be a useful first step in finding interesting genes, in designing experiments and, in some cases, predicting function. However, this type of analysis is frequently uninformative. For example, over one-half of new ORFs in *S. cerevisiae* have no known function (6). If this is the case in a well studied organism such as yeast, the problem will be even worse in organisms that are less well studied or less manipulable. A large, experimentally determined gene function database would make homology/motif searches much more useful.

Experimental analysis must be performed to thoroughly understand the biological function of a gene product. Scaling up from classical "cottage industry" one-gene-oriented approaches to whole-genome analysis would be very expensive and laborious. It is clear that novel strategies are necessary to efficiently pursue the next phase of the genome projects—whole-genome experimental analysis to explore gene expression, gene product function, and other genome functions. Model organisms, such as *S. cerevisiae*, will be extremely

important in the development of novel whole-genome analysis techniques and, subsequently, in improving our understanding of other more complex and less manipulable organisms.

The genome sequence can be systematically used as a tool to understand ORFs, gene product function, and other genome regions. Toward this end, a directed strategy has been developed for exploiting sequence information as a means of providing information about biological function (Fig. 1). Efforts have been directed toward the amplification of each predicted ORF or any other region of the genome ranging from a few base pairs to several kilobase pairs. There are many uses for these amplicons—they can be cloned into standard vectors or specialized expression vectors, or can be cloned into other specialized vectors such as those used for two-hybrid analysis. The amplicons can also be used directly by, for example, arraying onto glass for expression analysis, for DNA binding assays, or for any direct DNA assay (7). As a pilot study, synthetic primers were made on the 96-well automated multiplex oligonucleotide synthesizer (AMOS) instrument (8) (Fig. 2). These oligonucleotides were used to amplify each ORF on yeast chromosome V. The current version of this instrument can synthesize three plates of 96 oligonucleotides each (25 bases) in an 8-hr day. The amplification of the entire set of PCR products was then analyzed by gel electrophoresis (Fig. 3). Successful amplification of the proper length product on the first attempt was 95%. This project demonstrates that one can go directly from sequence information to biological analysis in a truly automated, totally directed manner.

These amplicons can be incorporated directly in arrays or the amplicons can be cloned. If the amplicons are to be cloned, novel sequences can be incorporated at the 5' end of the oligonucleotide to facilitate cloning. One potential problem with cloning PCR products is that the cloned amplicons may contain sequence alterations that diminish their utility. One option would be to resequence each individual amplicon. However, this is expensive, inefficient, and time consuming. A faster, more cost-effective, and more accurate approach is to apply comparative sequencing by denaturing HPLC (9). This method is capable of detecting a single base change in a 2-kb heteroduplex. Longer amplicons can be analyzed by use of appropriate restriction fragments. If any change is detected in a clone, an alternate clone of the same region can be analyzed. Modifying the system to allow high throughput analysis by denaturing HPLC is also relatively simple and straightforward.

If amplicons are used directly on arrays without cloning, it is important to note that, even if single PCR product bands are observed on gels, the PCR products will be contaminated with various amounts of other sequences. This contamination has the potential to affect the results in, for example, expression

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be hereby marked "advertisement" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

© 1997 by The National Academy of Sciences 0027-8424/97/948945-3\$2.00/0  
PNAS is available online at <http://www.pnas.org>.

<sup>†</sup>Present address: Synteni, Inc., 6519 Dumbarton Circle, Fremont, CA 94555.

<sup>§</sup>To whom reprint requests should be addressed at: Department of Biochemistry, Beckman Center, B400, Stanford University, Stanford, CA 94305-5307. e-mail: [gilbert@cmgm.stanford.edu](mailto:gilbert@cmgm.stanford.edu).

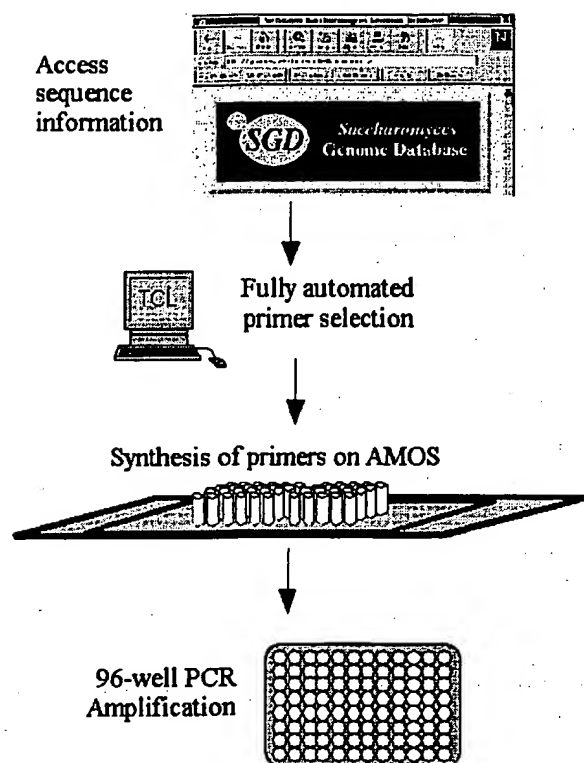


FIG. 1. Overview of systematic method for isolating individual genes. Sequence information is obtained automatically from sequence databases. The data are input into primer selection software specifically designed to target ORFs as designated by database annotations. The output file containing the primer information is directly read by a high-throughput oligonucleotide synthesizer, which makes the oligonucleotides in 96-well plates (AMOS, automated multiplex oligonucleotide synthesizer). The forward and reverse primers are synthesized in the same location on separate plates to facilitate the downstream handling of primers. The amplicons are generated by PCR in 96-well plates as well.

analysis. On the other hand, direct use of the amplicons is much less labor intensive and greatly decreases the occurrence of mistakes in clone identification, a ubiquitous problem associated with large clone set archiving and retrieving.

Any large-scale effort to capture each ORF within a genome must rely on automation if cost is to be minimized while efficiency is maximized. Toward that end, primers targeting ORFs were designed automatically using simple new scripts and existing primer selection software. These script-selected primer sequences were directly read by the high-throughput synthesizer and the forward and reverse primers were synthesized in separate plates in corresponding wells to facilitate automated pipetting and PCR amplifications. Each of the resulting PCR products, generated with minimum labor, contains a known, unique ORF.

Large-scale genome analysis projects are dependent on newly emerging technologies to make the studies practical and economically feasible. For example, the cost of the primers, a significant issue in the past, has been reduced dramatically to make feasible this and other projects that require tens of thousands of oligonucleotides. Other methods of high-throughput analysis are also vital to the success of functional analysis projects, such as microarraying and oligonucleotide chip methods (10–14).

Changes in attitude are also required. One of the major costs of commercial oligonucleotides is extensive quality control such that virtually 100% of the supplied oligonucleotides are successfully synthesized and work for their intended purpose.

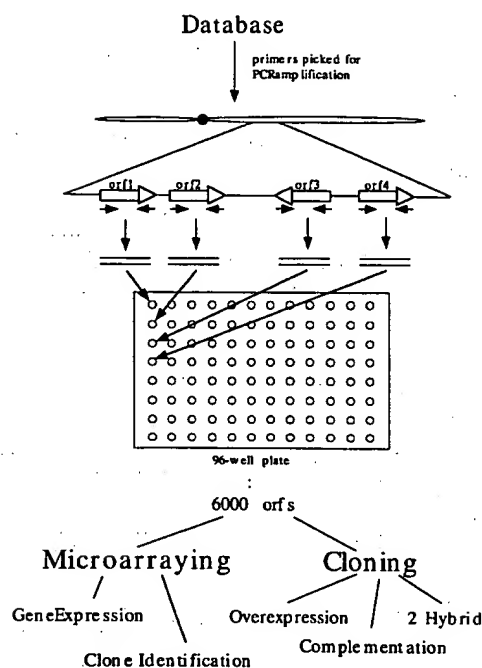


FIG. 2. Overall approach for using database of a genome to direct biological analysis. The synthesis of the 6,000 ORFs (orfs) for each gene of *S. cerevisiae* can be used in many applications utilizing both cloning and microarraying technology.

Considerable cost reduction can be obtained by simply decreasing the expected successful synthesis rate to 95–97%. One can then achieve faster and cheaper whole genome coverage by simply adding a single quality control at the end of the experiment and batching the failures for resynthesis.

The directed nature of the amplicon approach is of clear advantage. The sequence of each ORF is analyzed automatically, and unique specific primers are made to target each ORF. Thus, there is relatively little time or labor involved—for example, no random cloning and subsequent screening is required because each product is known. In the test system, primers for 240 ORFs from chromosome V were systematically synthesized, beginning from the left arm and continuing through to the right arm. At no point was there any manual analysis of sequence information to generate the collection. In many ways, now that the sequence is known, there is no need for the researcher to examine it.

These amplicons can be arrayed and expression analysis can be done on all arrayed ORFs with a single hybridization (10). Those ORFs that display significant differential expression patterns under a given selection are easily identified without the laborious task of searching for and then sequencing a clone. Once scaled up, the procedure provides even greater returns on effort, because a single hybridization will ultimately provide a “snapshot” of the expression of all genes in the yeast genome. Thus, the limiting factor in whole genome analysis will not be the analysis process itself, but will instead be the ability of researchers to design and carry out experimental selections.

Current expression and genetic analysis technologies are geared toward the analysis of single genes and are ill suited to analyze numerous genes under many conditions. Additional difficulties with current technologies include: the effort and expense required to analyze expression and make mutants, the potential duplication of effort if done by different laboratories, and the possibility of conflicting results obtained from different laboratories. In contrast, whole genome analysis not only is more efficient, it also provides data of much higher quality; all genes are assayed and compared in parallel under exactly



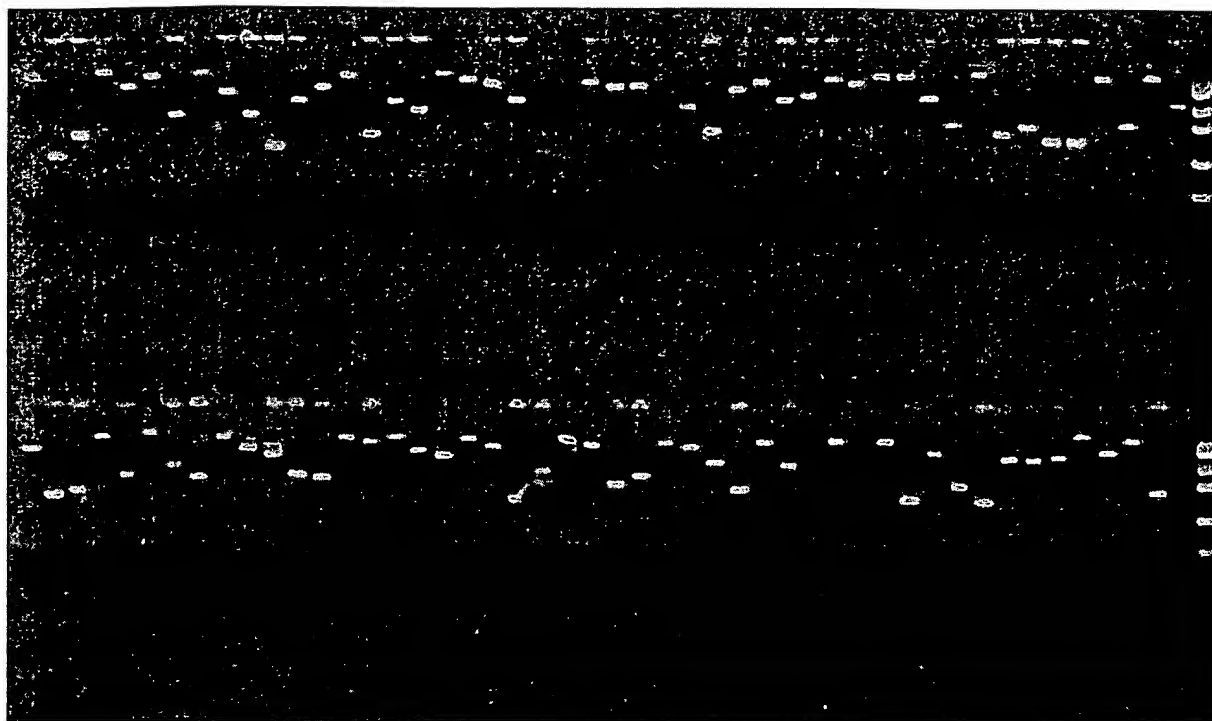


FIG. 3. Gel image of amplifications. Using the method described in Fig. 1, amplicons were generated for ORFs of *S. cerevisiae* chromosome V. One plate of 96 amplification reactions is shown.

the same conditions. In addition, amplicons have many applications beyond gene expression. For example, one recent approach is to incorporate a unique DNA sequence tag, synthesized as part of each gene specific primer, during amplification. The tags or molecular bar codes, when reintroduced into the organism as a gene deletion or as a gene clone, can be used much more efficiently than individual mutations or clones because pools of tagged mutants or transformants can be analyzed in parallel. This parallel analysis is possible because the tags are readily and quantitatively amplified even in complex mixtures of tags (13).

These ORF genome arrays and oligonucleotide tagged libraries can be used for many applications. Any conventional selection applied to a library that gives discrete or multiple products can use these technologies for a simple direct read-out. These include screens and selections for mutant complementation, overexpression suppression (15, 16), second-site suppressors, synthetic lethality, drug target overexpression (17), two-hybrid screens (18), genome mismatch scanning (19), or recombination mapping.

The genome projects have provided researchers with a vast amount of information. These data must be used efficiently and systematically to gain a truly comprehensive understanding of gene function and, more broadly, of the entire genome which can then be applied to other organisms. Such global approaches are essential if we are to gain an understanding of the living cell. This understanding should come from the viewpoint of the integration of complex regulatory networks, the individual roles and interactions of thousands of functional gene products, and the effect of environmental changes on both gene regulatory networks and the roles of all gene products. The time has come to switch from the analysis of a single gene to the analysis of the whole genome.

Support was provided by National Institutes of Health Grants R37H60198 and P01H600205.

1. Fleischmann, R. D., Adams, M. D., White, O., Clayton, R. A., Kirkness, E. F., *et al.* (1995) *Science* 269, 496–512.
2. Fraser, C. M., Gocayne, J. D., White, O., Adams, M. D., Clayton, R. A., *et al.* (1995) *Science* 270, 397–403.
3. Bult, C. J., White, O., Olsen, G. J., Zhou, L., Fleischmann, R. D., *et al.* (1996) *Science* 273, 1058–1073.
4. Sulston, J., Du, Z., Thomas, K., Wilson, R., Hillier, L., Staden, R., Halloran, N., Green, P., Thierry-Mieg, J., Qiu, L., Dear, S., Coulson, A., Craxton, M., Durbin, R., Berks, M., Metzstein, M., Hawkins, T., Ainscough, R. & Waterston, R. (1992) *Nature (London)* 356, 37–41.
5. Newman, T., de Bruijn, F. J., Green, P., Keegstra, K., Kende, H., *et al.* (1994) *Plant Physiol.* 106, 1241–1255.
6. Oliver, S. (1996) *Nature (London)* 379, 597–600.
7. Lashkari, D. A. (1996) Ph.D. dissertation (Stanford Univ., Stanford, CA).
8. Lashkari, D. A., Hunicke-Smith, S. P., Norgren, R. M., Davis, R. W. & Brennan, T. (1995) *Proc. Natl. Acad. Sci. USA* 92, 7912–7915.
9. Oefner, P. J. & Underhill, P. A. (1995) *Am. J. Hum. Genet.* 57, A266.
10. Schena, M., Shalon, D., Davis, R. W. & Brown, P. O. (1995) *Science* 270, 467–470.
11. Fodor, S. P., Read, J. L., Pirrung, M. C., Stryer, L., Lu, A. T. & Solas, D. (1991) *Science* 251, 767–773.
12. Chee, M., Yang, R., Hubbell, E., Berno, A., Huang, X. C., Stern, D., Winkler, J., Lockhart, D. J., Morris, M. S. & Fodor, S. P. (1996) *Science* 274, 610–614.
13. Shoemaker, D. D., Lashkari, D. A., Morris, D., Mittmann, M. & Davis, R. W. (1996) *Nat. Genet.* 14, 450–456.
14. Smith, V., Chou, K., Lashkari, D., Botstein, D. & Brown, P. O. (1996) *Science* 274, 2069–2074.
15. Magdolen, V., Drubin, D. G., Mages, G. & Bandlow, W. (1993) *FEBS Lett.* 316, 41–47.
16. Ramer, S. W., Elledge, S. J. & Davis, R. W. (1992) *Proc. Natl. Acad. Sci. USA* 89, 11589–11593.
17. Rine, J., Hansen, W., Hardeman, E. & Davis, R. W. (1983) *Proc. Natl. Acad. Sci. USA* 80, 6750–6754.
18. Fields, S. & Song, O. (1989) *Nature (London)* 340, 245–246.
19. Nelson, S. F., McCusker, J. H., Sander, M. A., Kee, Y., Modrich, P. & Brown, P. O. (1994) *Nat. Genet.* 4, 11–18.

## Microarrays and Toxicology: The Advent of Toxicogenomics

Emile F. Nuwaysir,<sup>1</sup> Michael Bittner,<sup>2</sup> Jeffrey Trent,<sup>2</sup> J. Carl Barrett,<sup>1</sup> and Cynthia A. Afshari<sup>1</sup>

<sup>1</sup>Laboratory of Molecular Carcinogenesis, National Institute of Environmental Health Sciences, Research Triangle Park, North Carolina

<sup>2</sup>Laboratory of Cancer Genetics, National Human Genome Research Institute, Bethesda, Maryland

The availability of genome-scale DNA sequence information and reagents has radically altered life-science research. This revolution has led to the development of a new scientific subdiscipline derived from a combination of the fields of toxicology and genomics. This subdiscipline, termed toxicogenomics, is concerned with the identification of potential human and environmental toxicants, and their putative mechanisms of action, through the use of genomics resources. One such resource is DNA microarrays or "chips," which allow the monitoring of the expression levels of thousands of genes simultaneously. Here we propose a general method by which gene expression, as measured by cDNA microarrays, can be used as a highly sensitive and informative marker for toxicity. Our purpose is to acquaint the reader with the development and current state of microarray technology and to present our view of the usefulness of microarrays to the field of toxicology. *Mol. Carcinog.* 24:153-159, 1999. © 1999 Wiley-Liss, Inc.

**Key words:** toxicology; gene expression; animal bioassay

### INTRODUCTION

Technological advancements combined with intensive DNA sequencing efforts have generated an enormous database of sequence information over the past decade. To date, more than 3 million sequences, totaling over 2.2 billion bases [1], are contained within the GenBank database, which includes the complete sequences of 19 different organisms [2]. The first complete sequence of a free-living organism, *Haemophilus influenzae*, was reported in 1995 [3] and was followed shortly thereafter by the first complete sequence of a eukaryote, *Saccharomyces cerevisiae* [4]. The development of dramatically improved sequencing methodologies promises that complete elucidation of the *Homo sapiens* DNA sequence is not far behind [5].

To exploit more fully the wealth of new sequence information, it was necessary to develop novel methods for the high-throughput or parallel monitoring of gene expression. Established methods such as northern blotting, RNase protection assays, S1 nuclease analysis, plaque hybridization, and slot blots do not provide sufficient throughput to effectively utilize the new genomics resources. Newer methods such as differential display [6], high-density filter hybridization [7,8], serial analysis of gene expression [9], and cDNA- and oligonucleotide-based microarray "chip" hybridization [10-12] are possible solutions to this bottleneck. It is our belief that the microarray approach, which allows the monitoring of expression levels of thousands of genes simultaneously, is a tool of unprecedented power for use in toxicology studies.

Almost without exception, gene expression is altered during toxicity, as either a direct or indirect result of toxicant exposure. The challenge facing toxicologists is to define, under a given set of experimental conditions, the characteristic and specific pattern of gene expression elicited by a given toxicant. Microarray technology offers an ideal platform for this type of analysis and could be the foundation for a fundamentally new approach to toxicology testing.

### MICROARRAY DEVELOPMENT AND APPLICATIONS

#### cDNA Microarrays

In the past several years, numerous systems were developed for the construction of large-scale DNA arrays. All of these platforms are based on cDNAs or oligonucleotides immobilized to a solid support. In the cDNA approach, cDNA (or genomic) clones of interest are arrayed in a multi-well format and amplified by polymerase chain reaction. The products of this amplification, which are usually 500- to 2000-bp clones from the 3' regions of the genes of interest, are then spotted onto solid support by using high-speed robotics. By using this method, microarrays of up to 10 000 clones can be generated by spotting onto a glass substrate

\*Correspondence to: Laboratory of Molecular Carcinogenesis, National Institute of Environmental Health Sciences, 111 Alexander Drive, Research Triangle Park, NC 27709.

Received 8 December 1998; Accepted 5 January 1999

Abbreviations: PAH, polycyclic aromatic hydrocarbon; NIEHS, National Institute of Environmental Health Sciences.

[13,14]. Sample detection for microarrays on glass involves the use of probes labeled with fluorescent or radioactive nucleotides.

Fluorescent cDNA probes are generated from control and test RNA samples in single-round reverse-transcription reactions in the presence of fluorescently tagged dUTP (e.g., Cy3-dUTP and Cy5-dUTP), which produces control and test products labeled with different fluorophores. The cDNAs generated from these two populations, collectively termed the "probe," are then mixed and hybridized to the array under a glass coverslip [10,11,15]. The fluorescent signal is detected by using a custom-designed scanning confocal microscope equipped with a motorized stage and lasers for fluor excitation [10,11,15]. The data are analyzed with custom digital image analysis software that determines for each DNA feature the ratio of fluor 1 to fluor 2, corrected for local background [16,17]. The strength of this approach lies in the ability to label RNAs from control and treated samples with different fluorescent nucleotides, allowing for the simultaneous hybridization and detection of both populations on one microarray. This method eliminates the need to control for hybridization between arrays. The research groups of Drs. Patrick Brown and Ron Davis at Stanford University spearheaded the effort to develop this approach, which has been successfully applied to studies of *Arabidopsis thaliana* RNA [10], yeast genomic DNA [15], tumorigenic versus non-tumorigenic human tumor cell lines [11], human T-cells [18], yeast RNA [19], and human inflammatory disease-related genes [20]. The most dramatic result of this effort was the first published account of gene expression of an entire genome, that of the yeast *Saccharomyces cerevisiae* [21].

In an alternative approach, large numbers of cDNA clones can be spotted onto a membrane support, albeit at a lower density [7,22]. This method is useful for expression profiling and large-scale screening and mapping of genomic or cDNA clones [7,22-24]. In expression profiling on filter membranes, two different membranes are used simultaneously for control and test RNA hybridizations, or a single membrane is stripped and reprobed. The signal is detected by using radioactive nucleotides and visualized by phosphorimager analysis or autoradiography. Numerous companies now sell such cDNA membranes and software to analyze the image data [25-27].

#### Oligonucleotide Microarrays

Oligonucleotide microarrays are constructed either by spotting prefabricated oligos on a glass support [13] or by the more elegant method of direct in situ oligo synthesis on the glass surface by photolithography [28-30]. The strength of this approach lies in its ability to discriminate DNA molecules based on single base-pair difference. This allows the application of this method to the fields of medical diagnos-

tics, pharmacogenetics, and sequencing by hybridization as well as gene-expression analysis.

Fabrication of oligonucleotide chips by photolithography is theoretically simple but technically complex [29,30]. The light from a high-intensity mercury lamp is directed through a photolithographic mask onto the silica surface, resulting in deprotection of the terminal nucleotides in the illuminated regions. The entire chip is then reacted with the desired free nucleotide, resulting in selected chain elongation. This process requires only  $4n$  cycles (where  $n$  = oligonucleotide length in bases) to synthesize a vast number of unique oligos, the total number of which is limited only by the complexity of the photolithographic mask and the chip size [29,31,32].

Sample preparation involves the generation of double-stranded cDNA from cellular poly(A)<sup>+</sup> RNA followed by antisense RNA synthesis in an in vitro transcription reaction with biotinylated or fluor-tagged nucleotides. The RNA probe is then fragmented to facilitate hybridization. If the indirect visualization method is used, the chips are incubated with fluor-linked streptavidin (e.g., phycoerythrin) after hybridization [12,33]. The signal is detected with a custom confocal scanner [34]. This method has been applied successfully to the mapping of genomic library clones [35], to de novo sequencing by hybridization [28,36], and to evolutionary sequence comparison of the *BRCA1* gene [37]. In addition, mutations in the cystic fibrosis [38] and *BRCA1* [39] gene products and polymorphisms in the human immunodeficiency virus-1 clade B protease gene [40] have been detected by this method. Oligonucleotide chips are also useful for expression monitoring [33] as has been demonstrated by the simultaneous evaluation of gene-expression patterns in nearly all open reading frames of the yeast strain *S. cerevisiae* [12]. More recently, oligonucleotide chips have been used to help identify single nucleotide polymorphisms in the human [41] and yeast [42] genomes.

#### THE USE OF MICROARRAYS IN TOXICOLOGY

##### Screening for Mechanism of Action

The field of toxicology uses numerous in vivo model systems, including the rat, mouse, and rabbit, to assess potential toxicity and these bioassays are the mainstay of toxicology testing. However, in the past several decades, a plethora of in vitro techniques have been developed to measure toxicity, many of which measure toxicant-induced DNA damage. Examples of these assays include the Ames test, the Syrian hamster embryo cell transformation assay, micronucleus assays, measurements of sister chromatid exchange and unscheduled DNA synthesis, and many others. Fundamental to all of these methods is the fact that toxicity is often preceded by, and results in, alterations in gene expression. In many cases, these changes in gene expression are a

far more sensitive, characteristic, and measurable endpoint than the toxicity itself. We therefore propose that a method based on measurements of the genome-wide gene expression pattern of an organism after toxicant exposure is fundamentally informative and complements the established methods described above.

We are developing a method by which toxicants can be identified and their putative mechanisms of action determined by using toxicant-induced gene expression profiles. In this method, in one or more defined model systems, dose and time-course parameters are established for a series of toxicants within a given prototypic class (e.g., polycyclic aromatic hydrocarbons (PAHs)). Cells are then treated with these agents at a fixed toxicity level (as measured by cell survival), RNA is harvested, and toxicant-induced gene expression changes are assessed by hybridization to a cDNA microarray chip (Figure 1). We have developed a custom DNA chip, called ToxChip v1.0, specifically for this purpose and will discuss it in more detail below. The changes in gene expression induced by the test agents in the model systems are analyzed, and the common set of changes unique to that class of toxicants, termed a toxicant signature, is determined.

This signature is derived by ranking across all experiments the gene-expression data based on rela-

tive fold induction or suppression of genes in treated samples versus untreated controls and selecting the most consistently different signals across the sample set. A different signature may be established for each prototypic toxicant class. Once the signatures are determined, gene-expression profiles induced by unknown agents in these same model systems can then be compared with the established signatures. A match assigns a putative mechanism of action to the test compound. Figure 2 illustrates this signature method for different types of oxidant stressors, PAHs, and peroxisome proliferators. In this example, the unknown compound in question had a gene-expression profile similar to that of the oxidant stressors in the database. We anticipate that this general method will also reveal cross talk between different pathways induced by a single agent (e.g., reveal that a compound has both PAH-like and oxidant-like properties). In the future, it may be necessary to distinguish very subtle differences between compounds within a very large sample set (e.g., thousands of highly similar structural isomers in a combinatorial chemistry library or peptide library). To generate these highly refined signatures, standard statistical clustering techniques or principal-component analysis can be used.

For the studies outlined in Figure 2, we developed the custom cDNA microarray chip ToxChip v1.0.

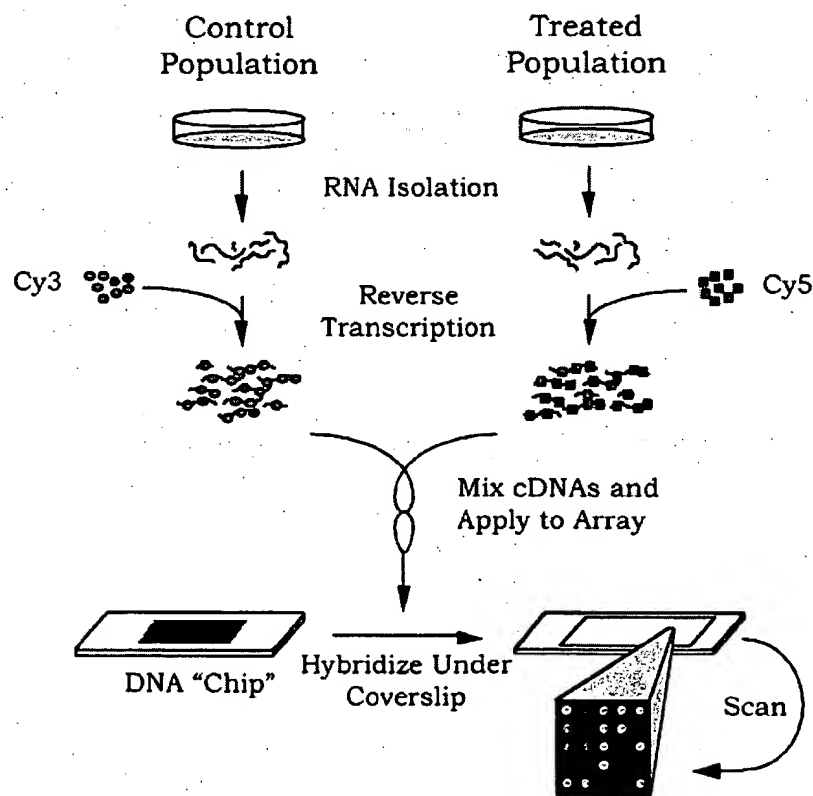


Figure 1. Simplified overview of the method for sample preparation and hybridization to cDNA microarrays. For illus-

trative purposes, samples derived from cell culture are depicted, although other sample types are amenable to this analysis.

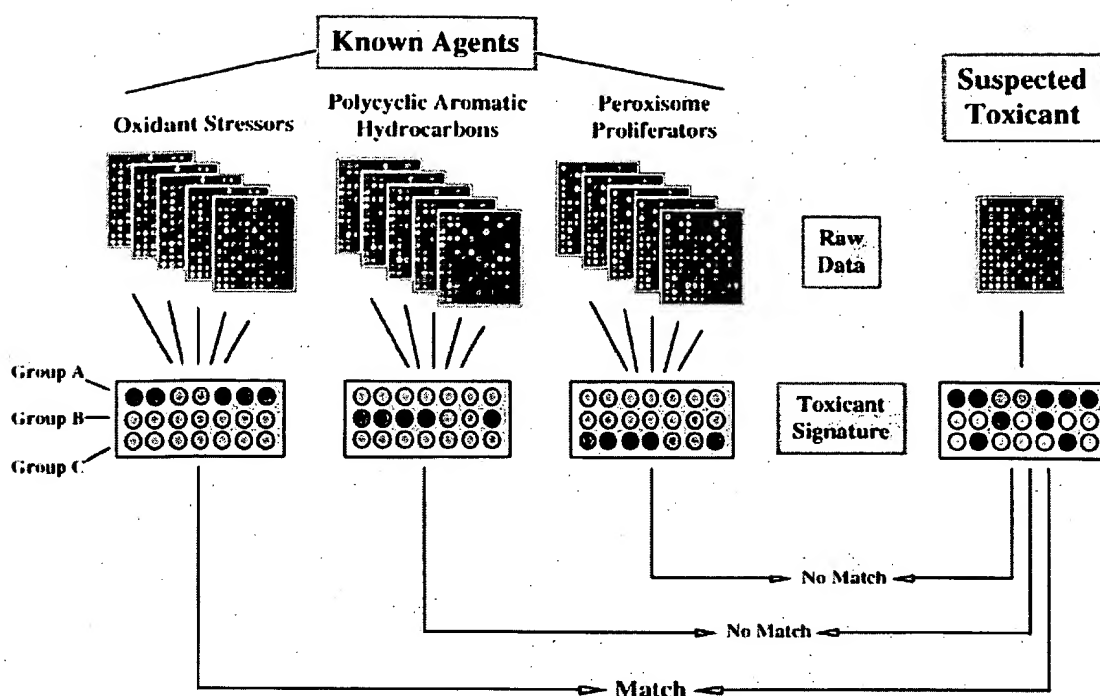


Figure 2. Schematic representation of the method for identification of a toxicant's mechanism of action. In this method, gene-expression data derived from exposure of model systems to known toxicants are analyzed, and a set of changes characteristic to that type of toxicant (termed the toxicant signature) is identified. As depicted, oxidant stressors produce

consistent changes in group A genes (indicated by red and green circles), but not group B or C genes (indicated by gray circles). The set of gene-expression changes elicited by the suspected toxicant is then compared with these characteristic patterns, and a putative mechanism of action is assigned to the unknown agent.

The 2090 human genes that comprise this subarray were selected for their well-documented involvement in basic cellular processes as well as their responses to different types of toxic insult. Included on this list are DNA replication and repair genes, apoptosis genes, and genes responsive to PAHs and dioxin-like compounds, peroxisome proliferators, estrogenic compounds, and oxidant stress. Some of the other categories of genes include transcription factors, oncogenes, tumor suppressor genes, cyclins, kinases, phosphatases, cell adhesion and motility genes, and homeobox genes. Also included in this group are 84 housekeeping genes, whose hybridization intensity is averaged and used for signal normalization of the other genes on the chip. To date, very few toxicants have been shown to have appreciable effects on the expression of these housekeeping genes. However, this housekeeping list will be revised if new data warrant the addition or deletion of a particular gene. Table 1 contains a general description of some of the different classes of genes that comprise ToxChip v1.0.

When a toxicant signature is determined, the genes within this signature are flagged within the database. When uncharacterized toxicants are then screened, the data can be quickly reformatted so that blocks of genes representing the different signatures

are displayed [11]. This facilitates rapid, visual interpretation of data. We are also developing ToxChip v2.0 and chips for other model systems, including rat, mouse, *Xenopus*, and yeast, for use in toxicology studies.

#### Animal Models in Toxicology Testing

The toxicology community relies heavily on the use of animals as model systems for toxicology testing. Unfortunately, these assays are inherently expensive, require large numbers of animals and take a long time to complete and analyze. Therefore, the National Institute of Environmental Health Sciences (NIEHS), the National Toxicology Program, and the toxicology community at large are committed to reducing the number of animals used, by developing more efficient and alternative testing methodologies. Although substantial progress has been made in the development of alternative methods, bioassays are still used for testing endpoints such as neurotoxicity, immunotoxicity, reproductive and developmental toxicology, and genetic toxicology. The rodent cancer bioassay is a particularly expensive and time-consuming assay, as it requires almost 4 yr, 1200 animals, and millions of dollars to execute and analyze [43]. In vitro experiments of the type outlined in Figure 2 might provide evidence that an unknown

Table 1. ToxChip v1.0: A Human cDNA Microarray Chip Designed to Detect Responses to Toxic Insult

Gene category	No. of genes on chip
Apoptosis	72
DNA replication and repair	99
Oxidative stress/redox homeostasis	90
Peroxisome proliferator responsive	22
Dioxin/PAH responsive	12
Estrogen responsive	63
Housekeeping	84
Oncogenes and tumor suppressor genes	76
Cell-cycle control	51
Transcription factors	131
Kinases	276
Phosphatases	88
Heat-shock proteins	23
Receptors	349
Cytochrome P450s	30

\*This list is intended as a general guide. The gene categories are not unique, and some genes are listed in multiple categories.

agent is (or is not) responsible for eliciting a given biological response. This information would help to select a bioassay more specifically suited to the agent in question or perhaps suggest that a bioassay is not necessary, which would dramatically reduce cost, animal use, and time.

The addition of microarray techniques to standard bioassays may dramatically enhance the sensitivity and interpretability of the bioassay and possibly reduce its cost. Gene-expression signatures could be determined for various types of tissue-specific toxicants, and new compounds could be screened for these characteristic signatures, providing a rapid and sensitive *in vivo* test. Also, because gene expression is often exquisitely sensitive to low doses of a toxicant, the combination of gene-expression screening and the bioassay might allow the use of lower toxicant doses, which are more relevant to human exposure levels, and the use of fewer animals. In addition, gene-expression changes are normally measured in hours or days, not in the months to years required for tumor development. Furthermore, microarrays might be particularly useful for investigating the relationship between acute and chronic toxicity and identifying secondary effects of a given toxicant by studying the relationship between the duration of exposure to a toxicant and the gene-expression profile produced. Thus, a bioassay that incorporates gene-expression signatures with traditional endpoints might be substantially shorter, use more realistic dose regimens, and cost substantially less than the current assays do.

These considerations are also relevant for branches of toxicology not related to human health and not using rodents as model systems, such as aquatic toxicology and plant pathology. Bioassays based on the flathead minnow, *Daphnia*, and *Arabidopsis* could

also be improved by the addition of microarray analysis. The combination of microarrays with traditional bioassays might also be useful for investigating some of the more intractable problems in toxicology research, such as the effects of complex mixtures and the difficulties in cross-species extrapolation.

#### Exposure Assessment, Environmental Monitoring, and Drug Safety

The currently used methods for assessment of exposure to chemical toxicants are based on measurement of tissue toxin levels or on surrogate markers of toxicity, termed biomarkers (e.g., peripheral blood levels of hepatic enzymes or DNA adducts). Because gene expression is a sensitive endpoint, gene expression as measured with microarray technology may be useful as a new biomarker to more precisely identify hazards and to assess exposure. Similarly, microarrays could be used in an environmental-monitoring capacity to measure the effect of potential contaminants on the gene-expression profiles of resident organisms. In an analogous fashion, microarrays could be used to measure gene-expression endpoints in subjects in clinical trials. The combination of these gene-expression data and more established toxic endpoints in these trials could be used to define highly precise surrogates of safety.

Gene-expression profiles in samples from exposed individuals could be compared to the profiles of the same individuals before exposure. From this information, the nature of the toxic exposure can be determined or a relative clinical safety factor estimated. In the future it may also be possible to estimate not only the nature but the dose of the toxicant for a given exposure, based on relative gene-expression levels. This general approach may be particularly appropriate for occupational-health applications, in which unexposed and exposed samples from the same individuals may be obtainable. For example, a pilot study of gene expression in peripheral-blood lymphocytes of Polish coke-oven workers exposed to PAHs (and many other compounds) is under consideration at the NIEHS. An important consideration for these types of studies is that gene expression can be affected by numerous factors, including diet, health, and personal habits. To reduce the effects of these confounding factors, it may be necessary to compare pools of control samples with pools of treated samples. In the future it may be possible to compare exposed sample sets to a national database of human-expression data, thus eliminating the need to provide an unexposed sample from the same individual. Efforts to develop such a national gene-expression database are currently under way [44,45]. However, this national database approach will require a better understanding of genome-wide gene expression across the highly diverse human population and of the effects of environmental factors on this expression.

### Alleles, Oligo Arrays, and Toxicogenetics

Gene sequences vary between individuals, and this variability can be a causative factor in human diseases of environmental origin [46,47]. A new area of toxicology, termed toxicogenetics, was recently developed to study the relationship between genetic variability and toxicant susceptibility. This field is not the subject of this discussion, but it is worthwhile to note that the ability of oligonucleotide arrays to discriminate DNA molecules based on single base-pair differences makes these arrays uniquely useful for this type of analysis. Recent reports demonstrated the feasibility of this approach [41,42]. The NIEHS has initiated the Environmental Genome Project to identify common sequence polymorphisms in 200 genes thought to be involved in environmental diseases [48]. In a pilot study on the feasibility of this application to the Environmental Genome Project, oligonucleotide arrays will be used to resequence 20 candidate genes. This toxicogenetic approach promises to dramatically improve our understanding of interindividual variability in disease susceptibility.

### FUTURE PRIORITIES

There are many issues that must be addressed before the full potential of microarrays in toxicology research can be realized. Among these are model system selection, dose selection, and the temporal nature of gene expression. In other words, in which species, at what dose, and at what time do we look for toxicant-induced gene expression? If human samples are analyzed, how variable is global gene expression between individuals, before and after toxicant exposure? What are the effects of age, diet, and other factors on this expression? Experience, in the form of large data sets of toxicant exposures, will answer these questions.

One of the most pressing issues for array scientists is the construction of a national public database (linked to the existing public databases) to serve as a repository for gene-expression data. This relational database must be made available for public use, and researchers must be encouraged to submit their expression data so that others may view and query the information. Researchers at the National Institutes of Health have made laudable progress in developing the first generation of such a database [44,45]. In addition, improved statistical methods for gene clustering and pattern recognition are needed to analyze the data in such a public database.

The proliferation of different platforms and methods for microarray hybridizations will improve sample handling and data collection and analysis and reduce costs. However, the variety of microarray methods available will create problems of data compatibility between platforms. In addition, the near-infinite variety of experimental conditions under

which data will be collected by different laboratories will make large-scale data analysis extremely difficult. To help circumvent these future problems, a set of standards to be included on all platforms should be established. These standards would facilitate data entry into the national database and serve as reference points for cross-platform and inter-laboratory data analysis.

Many issues remain to be resolved, but it is clear that new molecular techniques such as microarray hybridization will have a dramatic impact on toxicology research. In the future, the information gathered from microarray-based hybridization experiments will form the basis for an improved method to assess the impact of chemicals on human and environmental health.

### ACKNOWLEDGMENTS

The authors would like to thank Drs. Robert Maronpot, George Lucier, Scott Masten, Nigel Walker, Raymond Tennant, and Ms. Theodora Deverenux for critical review of this manuscript. EFN was supported in part by NIEHS Training Grant #ES07017-24.

### REFERENCES

1. <http://www.ncbi.nlm.nih.gov/Web/Genbank/index.html>
2. <http://www.ncbi.nlm.nih.gov/Entrez/Genome/org.html>
3. Fleischmann RD, Adams MD, White O, et al. Whole-genome random sequencing and assembly of *Haemophilus influenzae* Rd. *Science* 1995;269:496-512.
4. Goffeau A, Barrell BG, Bussey H, et al. Life with 6000 genes. *Science* 1996;274:546, 563-567.
5. <http://www.perkin-elmer.com/press/prc5448.html>
6. Liang P, Pardee AB. Differential display of eukaryotic messenger RNA by means of the polymerase chain reaction. *Science* 1992;257:967-971.
7. Pietu G, Alibert O, Guichard V, et al. Novel gene transcripts preferentially expressed in human muscles revealed by quantitative hybridization of a high density cDNA array. *Genome Res* 1996;6:492-503.
8. Zhao ND, Hashida H, Takahashi N, Misumi Y, Sakaki Y. High-density cDNA filter analysis—A novel approach for large-scale, quantitative analysis of gene expression. *Gene* 1995;156:207-213.
9. Velculescu VE, Zhang L, Vogelstein B, Kinzler KW. Serial analysis of gene expression. *Science* 1995;270:484-487.
10. Schena M, Shalon D, Davis RW, Brown PO. Quantitative monitoring of gene-expression patterns with a complementary DNA microarray. *Science* 1995;270:467-470.
11. DeRisi J, Penland L, Brown PO, et al. use of a cDNA microarray to analyse gene expression patterns in human cancer. *Nat Genet* 1996;14:457-460.
12. Wodicka L, Dong HL, Mittmann M, Ho MH, Lockhart DJ. Genome-wide expression monitoring in *Saccharomyces cerevisiae*. *Nat Biotechnol* 1997;15:1359-1367.
13. Marshall A, Hodgson J. DNA chips: An array of possibilities. *Nat Biotechnol* 1998;16:27-31.
14. <http://www.synteni.com>
15. Shalon D, Smith SJ, Brown PO. A DNA microarray system for analyzing complex DNA samples using two-color fluorescent probe hybridization. *Genome Res* 1996;6:639-645.
16. Chen Y, Dougherty ER, Bittner ML. Ratio-based decisions and the quantitative analysis of cDNA microarray images. *Biomedical Optics* 1997;2:364-374.
17. Khan J, Simon R, Bittner M, et al. Gene expression profiling of alveolar rhabdomyosarcoma with cDNA microarrays. *Cancer Res* 1998;58:5009-5013.
18. Schena M, Shalon D, Heller R, Chai A, Brown PO, Davis RW. Parallel human genome analysis: Microarray-based expression monitoring of 1000 genes. *Proc Natl Acad Sci USA* 1996; 93:10614-10619.

19. Lashkari DA, DeRisi JL, McCusker JH, et al. Yeast microarrays for genome wide parallel genetic and gene expression analysis. *Proc Natl Acad Sci USA* 1997;94:13057-13062.
20. Heller RA, Schena M, Chai A, et al. Discovery and analysis of inflammatory disease-related genes using cDNA microarrays. *Proc Natl Acad Sci USA* 1997;94:2150-2155.
21. DeRisi JL, Iyer VR, Brown PO. Exploring the metabolic and genetic control of gene expression on a genomic scale. *Science* 1997;278:680-686.
22. Drmanac S, Stavropoulos NA, Labat I, et al. Gene-representing cDNA clusters defined by hybridization of 57,419 clones from infant brain libraries with short oligonucleotide probes. *Genomics* 1996;37:29-40.
23. Milosavljevic A, Savkovic S, Crkvenjakov R, et al. DNA sequence recognition by hybridization to short oligomers: Experimental verification of the method on the *E. coli* genome. *Genomics* 1996;37:77-86.
24. Drmanac S, Drmanac R. Processing of cDNA and genomic kilobase-size clones for massive screening, mapping and sequencing by hybridization. *Biotechniques* 1994;17:328-329, 332-336.
25. <http://www.resgen.com/>
26. <http://www.genomesystems.com/>
27. <http://www.clontech.com/>
28. Pease AC, Solas DA, Fodor SPA. Parallel synthesis of spatially addressable oligonucleotide probe matrices. Abstracts of Papers of the American Chemical Society 1992;203:34.
29. Pease AC, Solas D, Sullivan EJ, Cronin MT, Holmes CP, Fodor SPA. Light-generated oligonucleotide arrays for rapid DNA sequence analysis. *Proc Natl Acad Sci USA* 1994;91:5022-5026.
30. Fodor SPA, Read JL, Pirrung MC, Stryer L, Lu AT, Solas D. Light-directed, spatially addressable parallel chemical synthesis. *Science* 1991;251:767-773.
31. McGall G, Labadie J, Brock P, Wallraff G, Nguyen T, Hinsberg W. Light-directed synthesis of high-density oligonucleotide arrays using semiconductor photoresists. *Proc Natl Acad Sci USA* 1996;93:13555-13560.
32. Lipshutz RJ, Morris D, Chee M, et al. Using oligonucleotide probe arrays to access genetic diversity. *Biotechniques* 1995;19:442-447.
33. Lockhart DJ, Dong HL, Byrne MC, et al. Expression monitoring by hybridization to high-density oligonucleotide arrays. *Nat Biotechnol* 1996;14:1675-1680.
34. <http://www.mdyn.com/>
35. Sapolsky RJ, Lipshutz RJ. Mapping genomic library clones using oligonucleotide arrays. *Genomics* 1996;33:445-456.
36. Chee M, Yang R, Hubbell E, et al. Accessing genetic information with high-density DNA arrays. *Science* 1996;274:610-614.
37. Hacia JG, Makalowski W, Edgemon K, et al. Evolutionary sequence comparisons using high-density oligonucleotide arrays. *Nat Genet* 1998;18:155-158.
38. Cronin MT, Fucini RV, Kim SM, Masino RS, Wespi RM, Miyada CG. Cystic fibrosis mutation detection by hybridization to light-generated DNA probe arrays. *Hum Mutat* 1996;7:244-255.
39. Hacia JG, Brody LC, Chee MS, Fodor SPA, Collins FS. Detection of heterozygous mutations in BRCA1 using high density oligonucleotide arrays and two-colour fluorescence analysis. *Nat Genet* 1996;14:441-447.
40. Kozal MJ, Shah N, Shen NP, et al. Extensive polymorphisms observed in HIV-1 clade B protease gene using high-density oligonucleotide arrays. *Nat Med* 1996;2:753-759.
41. Wang DG, Fan JB, Siao CJ, et al. Large-scale identification, mapping, and genotyping of single-nucleotide polymorphisms in the human genome. *Science* 1998;280:1077-1082.
42. Winzler EA, Richards DR, Conway AR, et al. Direct allelic variation scanning of the yeast genome. *Science* 1998;281:1194-1197.
43. Chhabra RS, Huff JE, Schwetz BS, Selkirk J. An overview of prechronic and chronic toxicity carcinogenicity experimental-study designs and criteria used by the National Toxicology Program. *Environ Health Perspect* 1990;86:313-321.
44. Ermolaeva O, Rastogi M, Pruitt KD, et al. Data management and analysis for gene expression arrays. *Nat Genet* 1998;20:19-23.
45. <http://www.nhgri.nih.gov/DIR/LCG/15K/HTML/dbase.html>
46. Samson M, Libert F, Doranz BJ, et al. Resistance to HIV-1 infection in Caucasian individuals bearing mutant alleles of the CCR-5 chemokine receptor gene. *Nature* 1996;382:722-725.
47. Bell DA, Taylor JA, Paulson DF, Robertson CN, Mohler JL, Lucier GW. Genetic risk and carcinogen exposure—A common inherited defect of the carcinogen-metabolism gene glutathione-S-transferase M1 (Gstm1) that increases susceptibility to bladder cancer. *J Natl Cancer Inst* 1993;85:1159-1164.
48. <http://www.niehs.nih.gov/envgenom/home.html>





## Expression profiling in toxicology — potentials and limitations

Sandra Steiner \*, N. Leigh Anderson

*Large Scale Biology Corporation, 9620 Medical Center Drive, Rockville, MD 20850-3338, USA*

### Abstract

Recent progress in genomics and proteomics technologies has created a unique opportunity to significantly impact the pharmaceutical drug development processes. The perception that cells and whole organisms express specific inducible responses to stimuli such as drug treatment implies that unique expression patterns, molecular fingerprints, indicative of a drug's efficacy and potential toxicity are accessible. The integration into state-of-the-art toxicology of assays allowing one to profile treatment-related changes in gene expression patterns promises new insights into mechanisms of drug action and toxicity. The benefits will be improved lead selection, and optimized monitoring of drug efficacy and safety in pre-clinical and clinical studies based on biologically relevant tissue and surrogate markers. © 2000 Elsevier Science Ireland Ltd. All rights reserved.

**Keywords:** Proteomics; Genomics; Toxicology

### 1. Introduction

The majority of drugs act by binding to protein targets, most to known proteins representing enzymes, receptors and channels, resulting in effects such as enzyme inhibition and impairment of signal transduction. The treatment-induced perturbations provoke feedback reactions aiming to compensate for the stimulus, which almost always are associated with signals to the nucleus, resulting in altered gene expression. Such gene expression regulations account for both the

pharmacological action and the toxicity of a drug and can be visualized by either global mRNA or global protein expression profiling. Hence, for each individual drug, a characteristic gene regulation pattern, its molecular fingerprint, exists which bears valuable information on its mode of action and its mechanism of toxicity.

Gene expression is a multistep process that results in an active protein (Fig. 1). There exist numerous regulation systems that exert control at and after the transcription and the translation step. Genomics, by definition, encompasses the quantitative analysis of transcripts at the mRNA level, while the aim of proteomics is to quantify gene expression further down-stream, creating a snapshot of gene regulation closer to ultimate cell function control.

\* Corresponding author. Tel.: +1-301-4245989; fax: +1-301-7624892.

E-mail address: steiner@lsbc.com (S. Steiner).

## 2. Global mRNA profiling

Expression data at the mRNA level can be produced using a set of different technologies such as DNA microarrays, reverse transcript imaging, amplified fragment length polymorphism (AFLP), serial analysis of gene expression (SAGE) and others. Currently, DNA microarrays are very popular and promise a great potential. On a typical array, each gene of interest is represented either by a long DNA fragment (200–2400 bp) typically generated by polymerase chain reaction (PCR) and spotted on a suitable substrate using robotics (Schena et al., 1995; Shalon et al., 1996) or by several short oligonucleotides (20–30 bp) synthesized directly onto a solid support using photolabile nucleotide chemistry (Fodor et al., 1991; Chee et al., 1996). From control and treated tissues, total RNA or mRNA is isolated and reverse transcribed in the presence of radioactive or fluorescent labeled nucleotides, and the labeled probes are then hybridized to the arrays. The intensity of the array signal is measured for each gene transcript by either autoradiography or laser scanning confocal microscopy. The ratio between the signals of control and treated samples reflect the relative drug-induced change in transcript abundance.

## 3. Global protein profiling

Global quantitative expression analysis at the protein level is currently restricted to the use of two-dimensional gel electrophoresis. This technique combines separation of tissue proteins by isoelectric focusing in the first dimension and by sodium dodecyl sulfate slab gel electrophoresis-based molecular weight separation on the second, orthogonal dimension (Anderson et al., 1991). The product is a rectangular pattern of protein spots that are typically revealed by Coomassie Blue, silver or fluorescent staining (Fig. 2). Protein spots are identified by mass spectrometry following generation of peptide mass fingerprints (Mann et al., 1993) and sequence tags (Wilkins et al., 1996). Similar to the mRNA approach, the ratio between the optical density of spots from control and treated samples are compared to search for treatment-related changes.

## 4. Expression data analysis

Bioinformatics forms a key element required to organize, analyze and store expression data from either source, the mRNA or the protein level. The overall objective, once a mass of high-quality

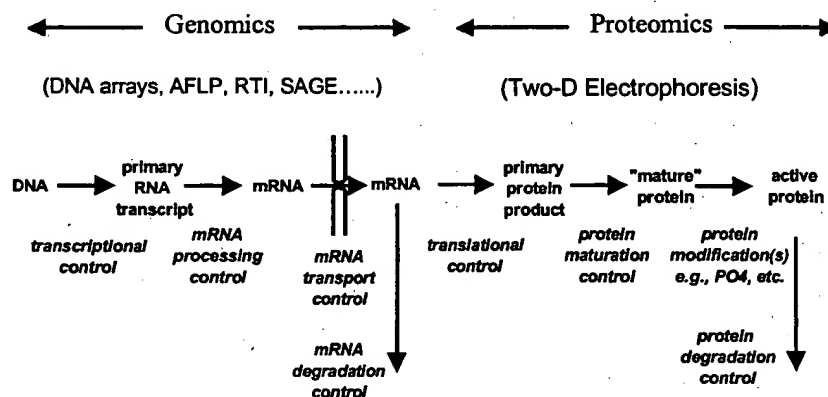


Fig. 1. Production of an active protein is a multistep process in which numerous regulation systems exert control at various stages of expression. Molecular fingerprints of drugs can be visualized through expression profiling at the mRNA level (genomics) using a variety of technologies and at the protein level (proteomics) using two-dimensional gel electrophoresis.

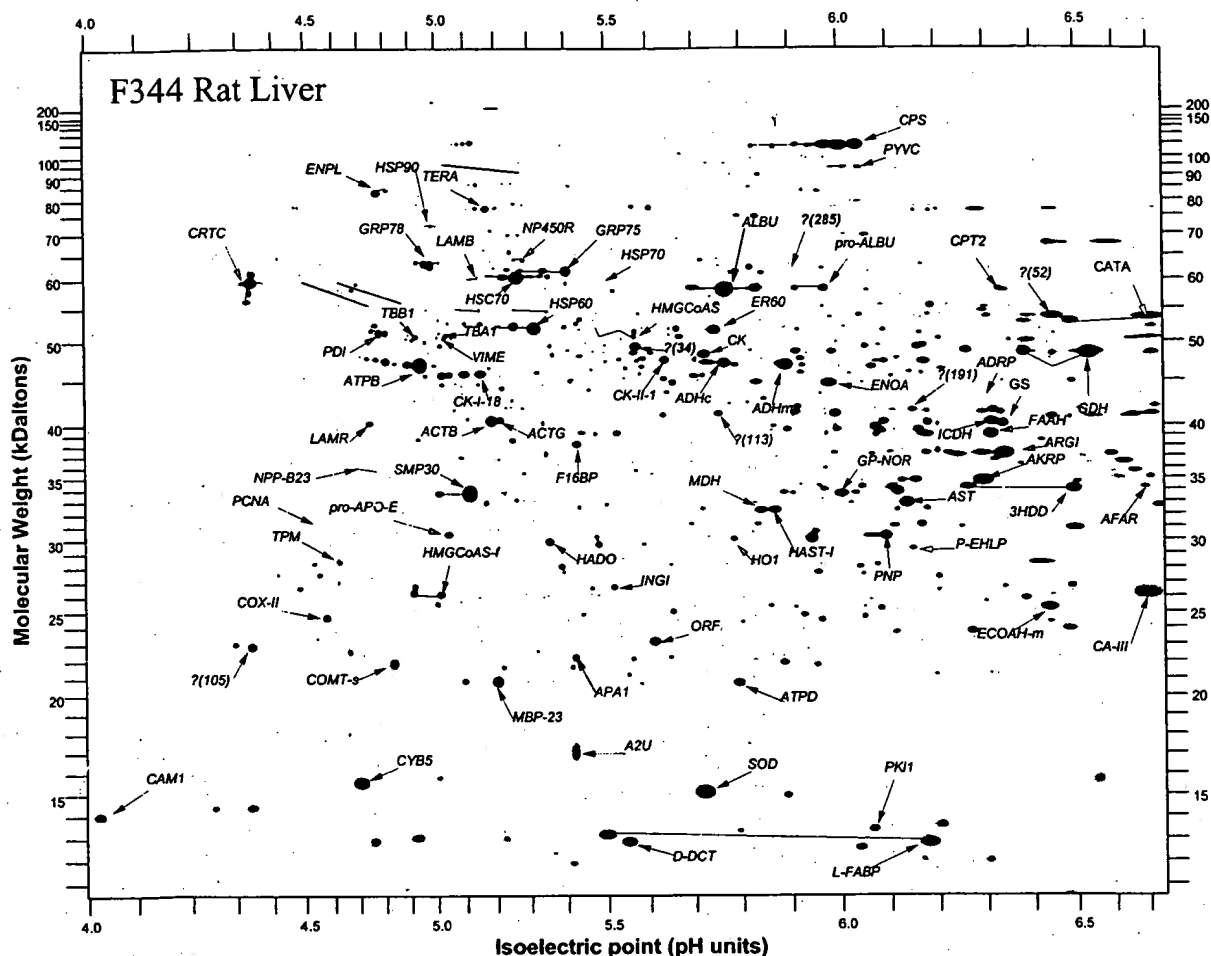


Fig. 2. Computerized representation of a Coomassie Blue stained two-dimensional gel electrophoresis pattern of Fischer F344 rat liver homogenate.

quantitative expression data has been collected, is to visualize complex patterns of gene expression changes, to detect pathways and sets of genes tightly correlated with treatment efficacy and toxicity, and to compare the effects of different sets of treatment (Anderson et al., 1996). As the drug effect database is growing, one may detect similarities and differences between the molecular fingerprints produced by various drugs, information that may be crucial to make a decision whether to refocus or extend the therapeutic spectrum of a drug candidate.

## 5. Comparison of global mRNA and protein expression profiling

There are several synergies and overlaps of data obtained by mRNA and protein expression analysis. Low abundant transcripts may not be easily quantified at the protein level using standard two-dimensional gel electrophoresis analysis and their detection may require prefractionation of samples. The expression of such genes may be preferably quantified at the mRNA level using techniques allowing PCR-mediated target amplifi-

cation. Tissue biopsy samples typically yield good quality of both mRNA and proteins; however, the quality of mRNA isolated from body fluids is often poor due to the faster degradation of mRNA when compared with proteins. RNA samples from body fluids such as serum or urine are often not very 'meaningful', and secreted proteins are likely more reliable surrogate markers for treatment efficacy and safety. Detection of post-translational modifications, events often related to function or nonfunction of a protein, is restricted to protein expression analysis and rarely can be predicted by mRNA profiling. Information on subcellular localization and translocation of proteins has to be acquired at the level of the protein in combination with sample prefractionation procedures. The growing evidence of a poor correlation between mRNA and protein abundance (Anderson and Seilhamer, 1997) further suggests that the two approaches, mRNA and protein profiling, are complementary and should be applied in parallel.

## 6. Expression profiling and drug development

Understanding the mechanisms of action and toxicity, and being able to monitor treatment efficacy and safety during trials is crucial for the successful development of a drug. Mechanistic insights are essential for the interpretation of drug effects and enhance the chances of recognizing potential species specificities contributing to an improved risk profile in humans (Richardson et al., 1993; Steiner et al., 1996b; Aicher et al., 1998). The value of expression profiling further increases when links between treatment-induced expression profiles and specific pharmacological and toxic endpoints are established (Anderson et al., 1991, 1995, 1996; Steiner et al. 1996a). Changes in gene expression are known to precede the manifestation of morphological alterations, giving expression profiling a great potential for early compound screening, enabling one to select drug candidates with wide therapeutic windows reflected by molecular fingerprints indicative of high pharmacological potency and low toxicity (Arce et al., 1998). In later phases of drug devel-

opment, surrogate markers of treatment efficacy and toxicity can be applied to optimize the monitoring of pre-clinical and clinical studies (Doherty et al., 1998).

## 7. Perspectives

The basic methodology of safety evaluation has changed little during the past decades. Toxicity in laboratory animals has been evaluated primarily by using hematological, clinical chemistry and histological parameters as indicators of organ damage. The rapid progress in genomics and proteomics technologies creates a unique opportunity to dramatically improve the predictive power of safety assessment and to accelerate the drug development process. Application of gene and protein expression profiling promises to improve lead selection, resulting in the development of drug candidates with higher efficacy and lower toxicity. The identification of biologically relevant surrogate markers correlated with treatment efficacy and safety bears a great potential to optimize the monitoring of pre-clinical and clinical trials.

## References

- Aicher, L., Wahl, D., Arce, A., Grenet, O., Steiner, S., 1998. New insights into cyclosporine A nephrotoxicity by proteome analysis. *Electrophoresis* 19, 1998–2003.
- Anderson, N.L., Seilhamer, J., 1997. A comparison of selected mRNA and protein abundances in human liver. *Electrophoresis* 18, 533–537.
- Anderson, N.L., Esquer-Blasco, R., Hofmann, J.P., Anderson, N.G., 1991. A two-dimensional gel database of rat liver proteins useful in gene regulation and drug effects studies. *Electrophoresis* 12, 907–930.
- Anderson, L., Steele, V.K., Kelloff, G.J., Sharma, S., 1995. Effects of oltipraz and related chemoprevention compounds on gene expression in rat liver. *J. Cell. Biochem. Suppl.* 22, 108–116.
- Anderson, N.L., Esquer-Blasco, R., Richardson, F., Foxworthy, P., Eacho, P., 1996. The effects of peroxisome proliferators on protein abundances in mouse liver. *Toxicol. Appl. Pharmacol.* 137, 75–89.
- Arce, A., Aicher, L., Wahl, D., Esquer-Blasco, R., Anderson, N.L., Cordier, A., Steiner, S., 1998. Changes in the liver proteome of female Wistar rats treated with the hypoglycemic agent SDZ PGU 693. *Life Sci.* 63, 2243–2250.

- Chee, M., Yang, R., Hubbell, E., Berno, A., Huang, X.C., Stern, D., Winkler, J., Lockhart, D.J., Morris, M.S., Fodor, S.P., 1996. Accessing genetic information with high-density DNA arrays. *Science* 274, 610–614.
- Doherty, N.S., Littman, B.H., Reilly, K., Swindell, A.C., Buss, J., Anderson, N.L., 1998. Analysis of changes in acute-phase plasma proteins in an acute inflammatory response and in rheumatoid arthritis using two-dimensional gel electrophoresis. *Electrophoresis* 19, 355–363.
- Fodor, S.P., Read, J.L., Pirrung, M.C., Stryer, L., Lu, A.T., Solas, D., 1991. Light-directed, spatially addressable parallel chemical synthesis. *Science* 251, 767–773.
- Mann, M., Hojrup, P., Roepstorff, P., 1993. Use of mass spectrometric molecular weight information to identify proteins in sequence databases. *Biol. Mass Spectrom.* 22, 338–345.
- Richardson, F.C., Strom, S.C., Copple, D.M., Bendele, R.A., Probst, G.S., Anderson, N.L., 1993. Comparisons of protein changes in human and rodent hepatocytes induced by the rat-specific carcinogen, methapyrilene. *Electrophoresis* 14, 157–161.
- Schena, M., Shalon, D., Davis, R.W., Brown, P.O., 1995. Quantitative monitoring of gene expression patterns with a complementary DNA microarray. *Science* 251, 467–470.
- Shalon, D., Smith, S.J., Brown, P.O., 1996. A DNA microarray system for analyzing complex DNA samples using two-color fluorescent probe hybridization. *Genome Res.* 6, 639–645.
- Steiner, S., Wahl, D., Mangold, B.L.K., Robison, R., Raynackers, J., Meheus, L., Anderson, N.L., Cordier, A., 1996a. Induction of the adipose differentiation-related protein in liver of etomoxir treated rats. *Biochem. Biophys. Res. Commun.* 218, 777–782.
- Steiner, S., Aicher, L., Raymackers, J., Meheus, L., Esquer-Blasco, R., Anderson, L., Cordier, A., 1996b. Cyclosporine A mediated decrease in the rat renal calcium binding protein calbindin-D 28 kDa. *Biochem. Pharmacol.* 51, 253–258.
- Wilkins, M.R., Gasteiger, E., Sanchez, J.C., Appel, R.D., Hochstrasser, D.F., 1996. Protein identification with sequence tags. *Curr. Biol.* 6, 1543–1544.

## Application of DNA Arrays to Toxicology

John C. Rockett and David J. Dix

Reproductive Toxicology Division, National Health and Environmental Effects Research Laboratory, U.S. Environmental Protection Agency, Research Triangle Park, North Carolina, USA

DNA array technology makes it possible to rapidly genotype individuals or quantify the expression of thousands of genes on a single filter or glass slide, and holds enormous potential in toxicologic applications. This potential led to a U.S. Environmental Protection Agency-sponsored workshop titled "Application of Microarrays to Toxicology" on 7-8 January 1999 in Research Triangle Park, North Carolina. In addition to providing state-of-the-art information on the application of DNA or gene microarrays, the workshop catalyzed the formation of several collaborations, committees, and user's groups throughout the Research Triangle Park area and beyond. Potential application of microarrays to toxicologic research and risk assessment include genome-wide expression analyses to identify gene-expression networks and toxicant-specific signatures that can be used to define mode of action, for exposure assessment, and for environmental monitoring. Arrays may also prove useful for monitoring genetic variability and its relationship to toxicant susceptibility in human populations. **Key words:** DNA arrays, gene arrays, microarrays, toxicology. *Environ Health Perspect* 107:681-685 (1999). [Online 6 July 1999] <http://ehpnet1.niehs.nih.gov/docs/1999/107p681-685rockett/abstract.html>

Decoding the genetic blueprint is a dream that offers manifold returns in terms of understanding how organisms develop and function in an often hostile environment. With the rapid advances in molecular biology over the last 30 years, the dream has come a step closer to reality. Molecular biologists now have the ability to elucidate the composition of any genome. Indeed, almost 20 genomes have already been sequenced and more than 60 are currently under way. Foremost among these is the Human Genome Mapping Project. However, the genomes of a number of commonly used laboratory species are also under intensive investigation, including yeast, *Arabidopsis*, maize, rice, zebra fish, mouse, rat, and dog. It is widely expected that the completion of such programs will facilitate the development of many powerful new techniques and approaches to diagnosing and treating genetically and environmentally induced diseases which afflict mankind. However, the vast amount of data being generated by genome mapping will require new high-throughput technologies to investigate the function of the millions of new genes that are being reported. Among the most widely heralded of the new functional genomics technologies are DNA arrays, which represent perhaps the most anticipated new molecular biology technique since polymerase chain reaction (PCR).

Arrays enable the study of literally thousands of genes in a single experiment. The potential importance of arrays is enormous and has been highlighted by the recent publication of an entire *Nature Genetics* supplement dedicated to the technology (1). Despite this huge surge of interest, DNA arrays are still little used and largely unproven, as demonstrated by the high ratio of review and press articles to actual data papers. Even so, the potential they offer

has driven venture capitalists into a frenzy of investment and many new companies are springing up to claim a share of this rapidly developing market.

The U.S. Environmental Protection Agency (EPA) is interested in applying DNA array technology to ongoing toxicologic studies. To learn more about the current state of the technology, the Reproductive Toxicology Division (RTD) of the National Health and Environmental Effects Research Laboratory (NHEERL; Research Triangle Park, NC) hosted a workshop on "Application of Microarrays to Toxicology" on 7-8 January 1999 in Research Triangle Park, North Carolina. The workshop was organized by David Dix, Robert Kavlock, and John Rockett of the RTD/NHEERL. Twenty-two intramural and extramural scientists from government, academia, and industry shared information, data, and opinions on the current and future applications for this exciting new technology. The workshop had more than 150 attendees, including researchers, students, and administrators from the EPA, the National Institute of Environmental Health Sciences (NIEHS), and a number of other establishments from Research Triangle Park and beyond. Presentations ranged from the technology behind array production through the sharing of actual experimental data and projections on the future importance and applications of arrays. The information contained in the workshop presentations should provide aid and insight into arrays in general and their application to toxicology in particular.

### Array Elements

In the context of molecular biology, the word "array" is normally used to refer to a series of DNA or protein elements firmly attached in

a regular pattern to some kind of supportive medium. DNA array is often used interchangeably with gene array or microarray. Although not formally defined, microarray is generally used to describe the higher density arrays typically printed on glass chips. The DNA elements that make up DNA arrays can be oligonucleotides, partial gene sequences, or full-length cDNAs. Companies offering pre-made arrays that contain less than full-length clones normally use regions of the genes which are specific to that gene to prevent false positives arising through cross-hybridization. Sequence verification of cDNA clone identity is necessary because of errors in identifying specific clones from cDNA libraries and databases. Premade DNA arrays printed on membranes are currently or imminently available for human, mouse, and rat. In most cases they contain DNA sequences representing several thousand different sequence clusters or genes as delineated through the National Center for Biotechnology Information UniGene Project (2). Many of these different UniGene clusters (putative genes) are represented only by expressed sequence tags (ESTs).

### Array Printing

Arrays are typically printed on one of two types of support matrix. Nylon membranes are used by most off-the-shelf array providers such as Clontech Laboratories, Inc. (Palo Alto, CA), Genome Systems, Inc. (St. Louis, MO), and Research Genetics, Inc. (Huntsville, AL). Microarrays such as those produced by Affymetrix, Inc. (Santa Clara, CA), Incyte Pharmaceuticals, Inc. (Palo Alto, CA), and many do-it-yourself (DIY) arraying groups use glass wafers or slides. Although standard microscope slides may be used, they must be preprepared to facilitate sticking of the DNA to the glass. Several different

Address correspondence to J. Rockett, Reproductive Toxicology Division (MD-72), National Health and Environmental Effects Research Laboratory, U.S. EPA, Research Triangle Park, NC 27711 USA. Telephone: (919) 541-2678. Fax: (919) 541-4017. E-mail: [rockett.john@epa.gov](mailto:rockett.john@epa.gov)

The authors thank R. Kavlock for envisioning the application of array technology to toxicology at the U.S. Environmental Protection Agency. We also thank T. Wall and B. Deitz for administrative assistance.

This document has been reviewed in accordance with EPA policy and approved for publication. Mention of companies, trade names, or products does not signify endorsement of such by the EPA.

Received 23 March 1999; accepted 22 April 1999.

coatings have been successfully used, including silane and lysine. The coating of slides can easily be carried out in the laboratory, but many prefer the convenience of precoated slides available from suppliers.

Once the support matrix has been prepared, the DNA elements can be applied by several methods. Affymetrix, Inc., has developed a unique photolithographic technology for attaching oligonucleotides to glass wafers. More commonly, DNA is applied by either noncontact or contact printing. Noncontact printers can use thermal, solenoid, or piezoelectric technology to spray aliquots of solution onto the support matrix and may be used to produce slide or membrane-based arrays. Cartesian Technologies, Inc. (Irvine, CA) has developed nQUAD technology for use in its PixSys printers. The system couples a syringe pump with the microsolenoid valve, a combination that provides rapid quantitative dispensing of nanoliter volumes (down to 4.2 nL) over a variable volume range. A different approach to noncontact printing uses a solid pin and ring combination (Genetic Microsystems, Inc., Woburn, MA). This system (Figure 1) allows a broader range of sample, including cell suspensions and particulates, because the printing head cannot be blocked up in the same way as a spray nozzle. Fluid transfer is controlled in this system primarily by the pin dimensions and the force of deposition, although the nature of the support matrix and the sample will also affect transfer to some degree.

In contact printing, the pin head is dipped in the sample and then touched to the support matrix to deposit a small aliquot. Split pins were one of the first contact-printing devices to be reported and are the suggested format for DIY arrays, as described by Brown (3). Split pins are small metal pins with a precise groove cut vertically in the middle of the pin tip. In this system, 1–48 split pins are positioned in the pin-head. The split pins work by simple capillary action, not unlike a fountain pen—when the pin heads are dipped in the sample, liquid is drawn into the pin groove. A small (fixed) volume is then deposited each time the split pins are gently touched to the support matrix. Sample (100–500 pL depending on a variety of parameters) can be deposited on multiple slides before refilling is required, and array densities of  $> 2,500$  spots/cm<sup>2</sup> may be produced. The deposit volume depends on the split size, sample fluidity, and the speed of printing. Split pins are relatively simple to produce and can be made in-house if a suitable machine shop is available. Alternatively, they can be obtained directly from companies such as TeleChem International, Inc. (Sunnyvale, CA).

Irrespective of their source, printers should be run through a preprint sequence prior to producing the actual experimental

arrays; the first 100 or so spots of a new run tend to be somewhat variable. Factors effecting spot reproducibility include slide treatment homogeneity, sample differences, and instrument errors. Other factors that come into play include clean ejection of the drop and clogging (nQUAD printing) and mechanical variations and long-term alteration in print-head surface of solid and split pins. However, with careful preparation it is possible to get a coefficient of variance for spot reproducibility below 10%.

One potential printing problem is sample carryover. Repeated washing, blotting, and drying (vacuum) of print pins between samples is normally effective at reducing sample carryover to negligible amounts. Printing should also be carried out in a controlled environment. Humidified chambers are available in which to place printers. These help prevent dust contamination and produce a uniform drying rate, which is important in determining spot size, quality, and reproducibility.

In summary, although several printing technologies are available, none are particularly outstanding and the bottom line is that they are still in a relatively early stage of evolution.

### Array Hybridization

The hybridization protocol is, practically speaking, relatively straightforward and those with previous experience in blotting should have little difficulty. Array hybridizations are, in essence, reverse Southern/Northern blots—instead of applying a labeled probe to the target population of DNA/RNA, the labeled population is applied to the probe(s). With membrane-based arrays, the control and treated mRNA populations are normally converted to cDNA and labeled with isotope (e.g., <sup>32</sup>P) in the process. These labeled populations are then hybridized independently to parallel or serial arrays and the hybridization signal is detected with a phosphorimager. A less commonly used alternative to radioactive probes is enzymatic detection. The probe may be biotinylated, haptenylated, or have alkaline phosphatase/horseradish peroxidase attached. Hybridization is detected by enzymatic reaction yielding a color reaction (4). Differences in hybridization signals can be detected by eye or, more accurately, with the help of digital imaging and commercially available software. The labeling of the test populations for slide-based microarrays uses a slightly different approach. The probe typically consists of two samples of polyA<sup>+</sup> RNA (usually from a treated and a control population) that are converted to cDNA; in the process each is labeled with a different fluor. The independently labeled probes are then mixed together and hybridized to a single microarray slide and the resulting combined fluorescent signal is scanned. After

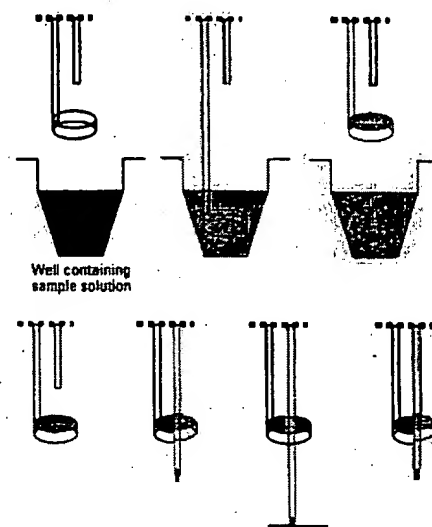


Figure 1. Genetic Microsystems (Woburn, MA) pin ring system for printing arrays. The pin ring combination consists of a circular open ring oriented parallel to the sample solution, with a vertical pin centered over the ring. When the ring is dipped into a solution and lifted, it withdraws an aliquot of sample held by surface tension. To spot the sample, the pin is driven down through the ring and a portion of the solution is transferred to the bottom of the pin. The pin continues to move downward until the pendant drop of solution makes contact with the underlying surface. The pin is then lifted, and gravity and surface tension cause deposition of the spot onto the array. Figure from Flowers et al. (14), with permission from Genetic Microsystems.

normalization, it is possible to determine the ratio of fluorescent signals from a single hybridization of a slide-based microarray.

cDNA derived from control and treated populations of RNA is most commonly hybridized to arrays, although subtractive hybridization or differential display reactions may also be used. Fluorophore- or radiolabeled nucleotides are directly incorporated into the cDNA in the process of converting RNA to cDNA. Alternatively, 5' end-labeled primers may be used for cDNA synthesis. These are labeled with a fluorophore for direct visualization of the hybridized array. Alternatively, biotin or a hapten may be attached to the primer, in which case fluor-labeled streptavidin or antibody must be applied before a signal can be generated. The most commonly used fluorophores at present are cyanine (Cy)3 and Cy5 (Amersham Pharmacia Biotech AB, Uppsala, Sweden). However, the relative expense of these fluorescent conjugates has driven a search for cheaper alternatives. Fluorescein, rhodamine, and Texas red have all been used, and companies such as Molecular Probes, Inc. (Eugene, OR) are developing a series of labeled nucleotides with a wide range of excitation and emission spectra which may prove to function as well as the Cy dyes.

## Analysis of DNA Microarrays

Membrane-based arrays are normally analyzed on film or with a phosphorimager, whereas chip-based arrays require more specialized scanning devices. These can be divided into three main groups: the charge-coupled device camera systems, the nonconfocal laser scanners, and the confocal laser scanners. The advantages and disadvantages of each system are listed in Table 1.

Because a typical spot on a microarray can contain  $> 10^8$  molecules, it is clear that a large variation in signal strength may occur. Current scanners cannot work across this many orders of magnitude (4 or 5 is more typical). However, the scanning parameters can normally be adjusted to collect more or less signal, such that two or three scans of the same array should permit the detection of rare and abundant genes.

When a microarray is scanned, the fluorescent images are captured by software normally included with the scanner. Several commercial suppliers provide additional software for quantifying array images, but the software tools are constantly evolving to meet the developing needs of researchers, and it is prudent to define one's own needs and clarify the exact capabilities of the software before its purchase. Issues that should be considered include the following:

- Can the software locate offset spots?
- Can it quantitate across irregular hybridization signals?
- Can the arrayed genes be programmed in for easy identification and location?
- Can the software connect via the Internet to databases containing further information on the gene(s) of interest?

One of the key issues raised at the workshop was the sensitivity of microarray technology. Experiments by General Scanning, Inc. (Watertown, MA), have shown that by using the Cy dyes and their scanner, signal can be detected down to levels of  $< 1$  fluor molecule per square micrometer, which translates to detecting a rare message at approximately one copy per cell or less.

## Array Applications

Although arrays are an emerging technology certain to undergo improvement and alteration, they have already been applied successfully to a number of model systems. Arrays are at their most powerful when they contain the entire genome of the species they are being used to study. For this reason, they have strong support among researchers utilizing yeast and *Caenorhabditis elegans* (5). The genomes of both of these species have been sequenced and, in the case of yeast, deposited onto arrays for examination of gene expression (6,7). With both of these species, it is relatively easy to perturb individual gene expression. Indeed, C.

Table 1. Advantages and disadvantages of different microarray scanning systems.

Nonconfocal laser scanner			
Advantages	Few moving parts	Relatively simple optics	Small depth of focus reduces artifacts
Disadvantages	Fast scanning of bright samples		May have high light collection efficiency
	Less appropriate for dim samples	Low light collection efficiency	Small depth of focus requires scanning precision
	Optical scatter can limit performance	Background artifacts not rejected	
Resolution typically low			

CCD, charge-coupled device.  
From Kawasaki (13).

*elegans* knockouts can be made simply by soaking the worms in an antisense solution of the gene to be knocked out.

By a process of systematic gene disruption, it is now possible to examine the cause and effect relationships between different genes in these simple organisms. This kind of approach should help elucidate biochemical pathways and genetic control processes, deconvolute polygenic interactions, and define the architecture of the cellular network. A simple case study of how this can be achieved was presented by Butow [University of Texas Southwestern Medical Center, Dallas, TX (Figure 2)]. Although it is the phenotypic result of a single gene knockout that is being examined, the effect of such perturbation will almost always be polygenic. Polygenic interactions will become increasingly important as researchers begin to move away from single gene systems when examining the nature of toxicologic responses to external stimuli. This is especially important in toxicology because the phenotype produced by a given environmental insult is never the result of the action of a single gene; rather, it is a complex interaction of one or multiple cellular pathways. Phenomena such as quantitative trait (the continuous variation of phenotype), epistasis (the effect of alleles of one or more genes on the expression of other genes), and penetrance (proportion of individuals of a given genotype that display a particular phenotype) will become increasingly evident and important as toxicologists push toward the ultimate goal of matching the responses of individuals to different environmental stimuli.

Analysis of the transcriptome (the expression level of all the genes in a given cell population) was a use of arrays addressed by several speakers. Unfortunately, current gene nomenclature is often confusing in that single genes are allocated multiple names (usually as a result of independent discovery by different laboratories), and there was a call for standardization of gene nomenclature. Nevertheless, once a transcriptome has been assembled it can then be transferred onto arrays and used to screen any chosen system. The EPA MicroArray Consortium (EPAMAC) is assembling testes

transcriptomes for human, rat, and mouse. In a slightly different approach, Nuwaysir et al. (8) describes how the NIEHS assembled what is effectively a "toxicological transcriptome"—a library of human and mouse genes that have previously been proven or implicated in responses to toxicologic insults. Clontech Laboratories, Inc. (Palo Alto, CA), has begun a similar process by developing stress/toxicology filter arrays of rat, mouse, and human genes. Thus, rather than being tissue or cell specific, these stress/toxicology arrays can be used across a variety of model systems to look for alterations in the expression of toxicologically important genes and define the new field of toxicogenomics. The potential to identify toxicant families based on tissue- or cell-specific gene expression could revolutionize drug testing. These molecular signatures or fingerprints could not only point to the possible toxicity/carcinogenicity of newly discovered compounds (Figure 3), but also aid in elucidating their mechanism of action through identification of gene expression networks. By extension, such signatures could provide easily identifiable biomarkers to assess the degree, time, and nature of exposure.

DNA arrays are primarily a tool for examining differential gene expression in a given model. In this context they are referred to as closed systems because they lack the ability of other differential expression technologies, e.g., differential display and subtractive hybridization, to detect previously unknown genes not present on the array. This would appear to limit the power of DNA arrays to the imaginations and preconceptions of the researcher in selecting genes previously characterized and thought to be involved in the model system. However, the various genome sequencing projects have created a new category of sequence—the EST—that has partially mollified this deficiency. ESTs are cDNAs expressed in a given tissue that, although they may share some degree of sequence similarity to previously characterized genes, have not been assigned specific genetic identity. By incorporating EST clones into an array, it is possible to monitor the expression of these unknown genes. This can enable the identification of previously uncharacterized genes that may have biologic

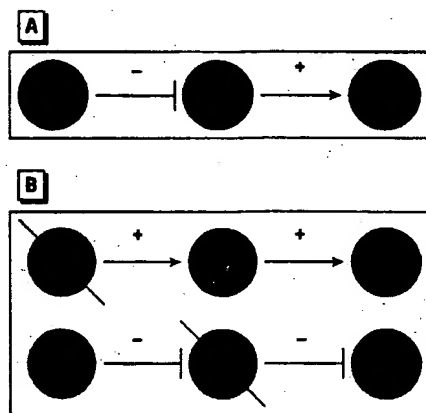


significance in the model system. Filter arrays from Research Genetics and slide arrays from Incyte Pharmaceuticals both incorporate large numbers of ESTs from a variety of species.

A further use of microarrays is the identification of single nucleotide polymorphisms (SNPs). These genomic variations are abundant—they occur approximately every 1 kb or so—and are the basis of restriction fragment length polymorphism analysis used in forensic analysis. Affymetrix, Inc., designed chips that contain multiple repeats of the same gene sequence. Each position is present with all four possible bases. After the hybridization of the sample, the degree of hybridization to the different sequences can be measured and the exact sequence of the target gene deduced. SNPs are thought to be of vital importance in drug metabolism and toxicology. For example, single base differences in the regulatory region or active site of some genes can account for huge differences in the activity of that gene. Such SNPs are thought to explain why some people are able to metabolize certain xenobiotics better than others. Thus, arrays provide a further tool for the toxicologist investigating the nature of susceptible subpopulations and toxicologic response.

There are still many wrinkles to be ironed out before arrays become a standard tool for toxicologists. The main issues raised at the workshop by those with hands-on experience were the following:

- Expense: the cost of purchasing/contracting this technology is still too great for many individual laboratories.



**Figure 2.** Potential effects of gene knockout within positively and negatively regulated gene expression networks.  $i_1$  is limiting in wild type for expression of  $i_2$ . (A) A simple, two-component, linear regulatory network operating on gene  $i_2$ , where  $i_1$  is a positive effector of  $i_2$  and  $j_n$  is either a positive or negative effector of  $i_1$ . This network could be deduced by examining the consequence of (B) deleting  $j_n$  on the expression of  $i_1$  and  $i_2$ , where the expression of  $i_2$  would be decreased or increased depending on whether  $j_n$  was a positive or negative regulator. These and other connected components of even greater complexity could be revealed by genome-wide expression analysis. From Butow (15).

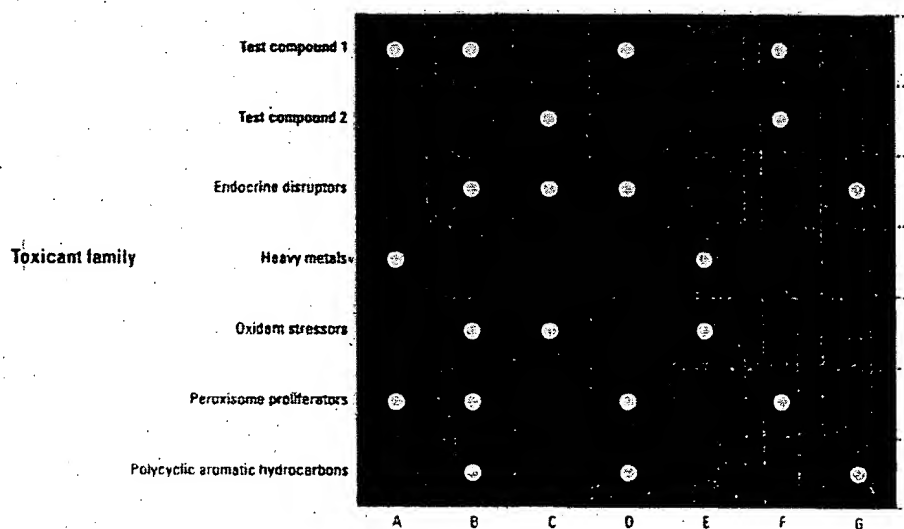
- Clones: the logistics of identifying, obtaining, and maintaining a set of nonredundant, non-contaminated, sequence-verified, species/cell/tissue/field-specific clones.
- Use of inbred strains: where whole-organism models are being used, the use of inbred strains is important to reduce the potentially confusing effects of the individual variation typically seen in outbred populations.
- Probe: the need for relatively large amounts of RNA, which limits the type of sample (e.g., biopsy) that can be used. Also, different RNA extraction methods can give different results.
- Specificity: the ability to discriminate accurately between closely related genes (e.g., the cytochrome p450 family) and splice variants.
- Quantitation: the quantitation of gene expression using gene arrays is still open to debate. One reason for this is the different incorporation of the labeling dyes. However, the main difficulty lies in knowing what to normalize against. One option is to include a large number of so-called housekeeping genes in the array. However, the expression of these genes often change depending on the tissue and the toxicant, so it is necessary to characterize the expression of these genes in the model system before utilizing them. This is clearly not a viable option when screening multiple new compounds. A second option is to include on the array genes from a nonrelated species (e.g., a plant gene on an animal array) and to spike the probe with synthetic RNA(s) complementary to the gene(s).
- Reproducibility: this is sometimes questionable, and a figure of approximately two or three repeats was used as the minimum number required to confirm initial findings.

Again, however, most people advocated the use of Northern blots or reverse transcriptase PCR to confirm findings.

- Sensitivity: concerns were voiced about the number of target molecules that must be present in a sample for them to be detected on the array.
- Efficiency: reproducible identification of 1.5- to 2-fold differences in expression was reported, although the number of genes that undergo this level of change and remain undetected is open to debate. It is important that this level of detection be ultimately achieved because it is commonly perceived that some important transcription factors and their regulators respond at such low levels. In most cases, 3- to 5-fold was the minimum change that most were happy to accept.
- Bioinformatics: perhaps the greatest concern was how to accurately interpret the data with the greatest accuracy and efficiency. The biggest headache is trying to identify networks of gene expression that are common to different treatments or doses. The amount of data from a single experiment is huge. It may be that, in the future, several groups individually equipped with specialized software algorithms for studying their favorite genes or gene systems will be able to share the same hybridized chips. Thus, arrays could usher in a new perspective on collaboration and the sharing of data.

## EPAMAC

Perhaps the main reason most scientists are unable to use array technology is the high cost involved, whether buying off-the-shelf membranes, using contract printing services, or



**Figure 3.** Gene expression profiles—also called fingerprints or signatures—of known toxicants or toxicant families may, in the future, be used to identify the potential toxicity of new drugs, etc. In this example, the genetic signature of test compound 1 is identical to that of known peroxisome proliferators, whereas that of test compound 2 does not match any known toxicant family. Based on these results, test compound 2 would be retained for further testing and test compound 1 would be eliminated.

producing chips in-house. In view of this, researchers at the RTD/NHEERL initiated the EPAMAC. This consortium brings together scientists from the EPA and a number of extramural labs with the aim of developing microarray capability through the sharing of resources and data. EPAMAC researchers are primarily interested in the developmental and toxicologic changes seen in testicular and breast tissue, and a portion of the workshop was set aside for EPAMAC members to share their ideas on how the experimental application of microarrays could facilitate their research. One of the central areas of interest to EPAMAC members is the effect of xenobiotics on male fertility and reproductive health. Of greatest concern is the effect of exposure during critical periods of development and germ cell differentiation (9), and how this may compromise sperm counts and quality following sexual maturation (10). As well as spermatogenic tissue, there is also interest in how residual mRNA found in mature sperm (11) could be used as an indicator of previous xenobiotic effects (it is easier to obtain a semen sample than a testicular biopsy). Arrays will be used to examine and compare the effect of exposure to heat and chemicals in testicular and epididymal gene expression profiles, with the aim of establishing relationships/associations between changes in developmental landmarks and the effects on sperm count and quality. Cluster, pattern, and other analysis of such data should help identify hidden relationships between genes that may reveal potential mechanisms of action and uncover roles for genes with unknown functions.

## Summary

The full impact of DNA arrays may not be seen for several years, but the interest shown at this regional workshop indicates the high level of interest that they foster. Apart from educating and advertising the various technologies in this field, this workshop brought together a number of researchers from the Research Triangle Park area who are already using DNA arrays. The interest in sharing ideas and experiences led to the initiation of a Triangle array user's group.

Array technology is still in its infancy. This means that the hardware is still improving and there is no current consensus for standard procedures, quantitation, and interpretation. Consistency in spotting and scanning arrays is not yet optimized, and this is one of the most critical requirements of any experiment. In addition, one of the dark regions of array technology—strife in the courts over who owns what portions of it—has further muddled the future and is a potential barrier toward the development of consensus procedures.

Perhaps the greatest hurdle for the application of arrays is the actual interpretation of data. No specialists in bioinformatics attended the workshop, largely because they are rare and because as yet no one seems clear on the best method of approaching data analysis and interpretation. Cross-referencing results from multiple experiments (time, dose, repeats, different animals, different species) to identify commonly expressed genes is a great challenge. In most cases, we are still a long way from understanding how the expression of gene *X* is related to the expression of gene *Y*, and ordering gene expression to delineate causal relationships.

To the ordinary scientist in the typical laboratory, however, the most immediate problem is a lack of affordable instrumentation. One can purchase premade membranes at relatively affordable prices. Although these may be useful in identifying individual genes to pursue in more detail using other methods, the numbers that would be required for even a small routine toxicology experiment prohibit this as a truly viable approach. For the toxicologist, there is a need to carry out multiple experiments—dose responses, time curves, multiple animals, and repeats. Glass-based DNA arrays are most attractive in this context because they can be prepared in large batches from the same DNA source and accommodate control and treated samples on the same chip. Another problem with current off-the-shelf arrays is that they often do not contain one or more of the particular genes a group is interested in. One alternative is to obtain and/or produce a set of custom clones and have contract printing of membranes or slides carried out by a company such as Genomic Solutions, Inc. (Ann Arbor, MI). This approach

is less expensive than laying out capital for one's own entire system, although at some point it might make economic sense to print one's own arrays.

Finally, DNA arrays are currently a team effort. They are a technology that uses a wide range of skills including engineering, statistics, molecular biology, chemistry, and bioinformatics. Because most individuals are skilled in only one or perhaps two of these areas, it appears that success with arrays may be best expected by teams of collaborators consisting of individuals having each of these skills.

Those considering array applications may be amused or goaded on by the following quote from *Fortune* magazine (12):

Microprocessors have reshaped our economy, spawned vast fortunes and changed the way we live. Gene chips could be even bigger.

Although this comment may have been designed to excite the imagination rather than accurately reflect the truth, it is fair to say that the age of functional genomics is upon us. DNA arrays look set to be an important tool in this new age of biotechnology and will likely contribute answers to some of toxicology's most fundamental questions.

## REFERENCES AND NOTES

1. The chipping forecast. *Nat Genet* 21(Suppl 1):3-60 (1999).
2. National Center for Biotechnology Information. The Unigene System. Available: [www.ncbi.nlm.nih.gov/Schuler/UniGene](http://www.ncbi.nlm.nih.gov/Schuler/UniGene) [cited 22 March 1999].
3. Brown PO. The Brown Lab. Available: <http://cmgm.Stanford.edu/pbrown> [cited 22 March 1999].
4. Chen JJ, Wu R, Yang PC, Huang JY, Sher YP, Han MH, Kao WC, Lee PJ, Chiu TF, Chang F, et al. Profiling expression patterns and isolating differentially expressed genes by cDNA microarray system with colorimetry detection. *Genomics* 51:313-324 (1998).
5. Ward S. DNA Microarray Technology to Identify Genes Controlling Spermatogenesis. Available: [www.mcb.arizona.edu/wardlab/microarray.html](http://www.mcb.arizona.edu/wardlab/microarray.html) [cited 22 March 1999].
6. Marton MJ, DeRisi JL, Bennett HA, Iyer VR, Meyer MR, Roberts CJ, Stoughton R, Burchard J, Slade O, Dai H, et al. Drug target validation and identification of secondary drug target effects using DNA microarrays. *Nat Med* 4:1293-1301 (1998).
7. Brown PO. The Full Yeast Genome on a Chip. Available: <http://cmgm.stanford.edu/pbrown/yeastchip.html> [cited 22 March 1999].
8. Nuwaysir EF, Bittner M, Trent J, Barrett JC, Afshari CA. Microarrays and toxicology: the advent of toxicogenomics. *Mol Carcinog* 24(3):153-159 (1999).
9. Hecht NB. Molecular mechanisms of male germ cell differentiation. *Bioessays* 20:555-561 (1998).
10. Zacharewski TR, Timothy R. Zacharewski. Available: [www.bchmsu.edu/faculty/zachar.htm](http://www.bchmsu.edu/faculty/zachar.htm) [cited 22 March 1999].
11. Kramer JA, Krawetz SA. RNA in spermatozoa: implications for the alternative haploid genome. *Mol Hum Reprod* 3:473-478 (1997).
12. Stipp D. Gene chip breakthrough. *Fortune*, March 31:56-73 (1997).
13. Kawasaki E (General Scanning Instruments, Inc., Watertown, MA). Unpublished data.
14. Flowers P, Overbeck J, Mace ML Jr, Pagliughi FM, Eggers WJE, Yonkers H, Honkanen P, Montagu J, Rose SD. Development and Performance of a Novel Microarraying System Based on Surface Tension Forces. Available: <http://www.geneticmicro.com/resources/html/coldspring.html> [cited 22 March 1999].
15. Butow R (University of Texas Medical Center, Dallas, TX). Unpublished data.

## SPEAKERS

Cindy Afshari NIEHS	Abdel Elkahouloun Research Genetics, Inc.
Linda Birnbaum U.S. EPA	Sue Fenton U.S. EPA
Ron Butow University of Texas Southwestern Medical Center	Norman Hecht University of Pennsylvania
Alex Chenchik Clontech Laboratories, Inc.	Pat Hurban Paradigm Genetics, Inc.
David Dix U.S. EPA	Bob Kavlock U.S. EPA
	Ernie Kawasaki General Scanning, Inc.

Steve Krawetz Wayne State University	Jim Samet U.S. EPA
Nick Mace Genetic Microsystems, Inc.	Sam Ward University of Arizona
Scott Mordecai Affymetrix, Inc.	Jeff Welch U.S. EPA
Kevin Morgan Glaxo Wellcome, Inc.	Reen Wu University of California at Davis
Elaine Poplin Research Genetics, Inc.	Tim Zacharewski Michigan State University
Don Rose Cartesian Technologies, Inc.	

Subject: RE: [Fwd: Toxicology Chip]

Date: Mon, 3 Jul 2000 08:09:45 -0400

From: "Afshari, Cynthia" <afshari@niehs.nih.gov>

To: "Diana Hamlet-Cox" <dianahc@incyte.com>

You can see the list of clones that we have on our 12K chip at  
<http://manuel.niehs.nih.gov/maps/guest/clonesrch.cfm>

We selected a subset of genes (2000K) that we believed critical to tox response and basic cellular processes and added a set of clones and ESTs to this. We have included a set of control genes (80+) that were selected by the NHGRI because they did not change across a large set of array experiments. However, we have found that some of these genes change significantly after tox treatments and are in the process of looking at the variation of each of these 80+ genes across our experiments.

Our chips are constantly changing and being updated and we hope that our data will lead us to what the toxchip should really be.

I hope this answers your question.

Cindy Afshari

> -----

> From: Diana Hamlet-Cox

> Sent: Monday, June 26, 2000 8:52 PM

> To: afshari@niehs.nih.gov

> Subject: [Fwd: Toxicology Chip]

>

> Dear Dr. Afshari,

>

> Since I have not yet had a response from Bill Grigg, perhaps he was not  
> the right person to contact.

>

> Can you help me in this matter? I don't need to know the sequences,  
> necessarily, but I would like very much to know what types of sequences  
> are being used, e.g., GPCRs (more specific?), ion channels, etc.

>

> Diana Hamlet-Cox

>

> ----- Original Message -----

> Subject: Toxicology Chip

> Date: Mon, 19 Jun 2000 18:31:48 -0700

> From: Diana Hamlet-Cox <dianahc@incyte.com>

> Organization: Incyte Pharmaceuticals

> To: grigg@niehs.nih.gov

>

> Dear Colleague:

>

> I am doing literature research on the use of expressed genes as  
> pharmacotoxicology markers, and found the Press Release dated February  
> 29, 2000 regarding the work of the NIEHS in this area. I would like to  
> know if there is a resource I can access (or you could provide?) that  
> would give me a list of the 12,000 genes that are on your Human ToxChip  
> Microarray. In particular, I am interested in the criteria used to  
> select sequences for the ToxChip, including any control sequences  
> included in the microarray.

>

> Thank you for your assistance in this request.

>

> Diana Hamlet-Cox, Ph.D.

> Incyte Genomics, Inc.

>

> --

>

> =====

> This email message is for the sole use of the intended recipient s and  
> may contain confidential and privileged information subject to  
> attorney-client privilege. Any unauthorized review, use, disclosure or  
> distribution is prohibited. If you are not the intended recipient,  
> please contact the sender by reply email and destroy all copies of the  
> original message.

> =====

>  
>  
>

## Assessing sequence comparison methods with reliable structurally identified distant evolutionary relationships

STEVEN E. BRENNER\*<sup>†‡</sup>, CYRUS CHOTHIA\*, AND TIM J. P. HUBBARD<sup>§</sup>

\*MRC Laboratory of Molecular Biology, Hills Road, Cambridge CB2 2QH, United Kingdom; and <sup>§</sup>Sanger Centre, Wellcome Trust Genome Campus, Hinxton, Cambs CB10 1SA, United Kingdom

Communicated by David R. Davies, National Institute of Diabetes, Bethesda, MD, March 16, 1998 (received for review November 12, 1997)

**ABSTRACT** Pairwise sequence comparison methods have been assessed using proteins whose relationships are known reliably from their structures and functions, as described in the SCOP database [Murzin, A. G., Brenner, S. E., Hubbard, T. & Chothia C. (1995) *J. Mol. Biol.* 247, 536–540]. The evaluation tested the programs BLAST [Altschul, S. F., Gish, W., Miller, W., Myers, E. W. & Lipman, D. J. (1990) *J. Mol. Biol.* 215, 403–410], WU-BLAST2 [Altschul, S. F. & Gish, W. (1996) *Methods Enzymol.* 266, 460–480], FASTA [Pearson, W. R. & Lipman, D. J. (1988) *Proc. Natl. Acad. Sci. USA* 85, 2444–2448], and SSEARCH [Smith, T. F. & Waterman, M. S. (1981) *J. Mol. Biol.* 147, 195–197] and their scoring schemes. The error rate of all algorithms is greatly reduced by using statistical scores to evaluate matches rather than percentage identity or raw scores. The E-value statistical scores of SSEARCH and FASTA are reliable: the number of false positives found in our tests agrees well with the scores reported. However, the P-values reported by BLAST and WU-BLAST2 exaggerate significance by orders of magnitude. SSEARCH, FASTA  $ktup = 1$ , and WU-BLAST2 perform best, and they are capable of detecting almost all relationships between proteins whose sequence identities are >30%. For more distantly related proteins, they do much less well; only one-half of the relationships between proteins with 20–30% identity are found. Because many homologs have low sequence similarity, most distant relationships cannot be detected by any pairwise comparison method; however, those which are identified may be used with confidence.

Sequence database searching plays a role in virtually every branch of molecular biology and is crucial for interpreting the sequences issuing forth from genome projects. Given the method's central role, it is surprising that overall and relative capabilities of different procedures are largely unknown. It is difficult to verify algorithms on sample data because this requires large data sets of proteins whose evolutionary relationships are known unambiguously and independently of the methods being evaluated. However, nearly all known homologs have been identified by sequence analysis (the method to be tested). Also, it is generally very difficult to know, in the absence of structural data, whether two proteins that lack clear sequence similarity are unrelated. This has meant that although previous evaluations have helped improve sequence comparison, they have suffered from insufficient, imperfectly characterized, or artificial test data. Assessment also has been problematic because high quality database sequence searching attempts to have both sensitivity (detection of homologs) and specificity (rejection of unrelated proteins); however, these complementary goals are linked such that increasing one causes the other to be reduced.

Sequence comparison methodologies have evolved rapidly, so no previously published tests have evaluated modern versions of programs commonly used. For example, parameters in BLAST (1) have changed, and WU-BLAST2 (2)—which produces gapped alignments—has become available. The latest version of FASTA (3) previously tested was 1.6, but the current release (version 3.0) provides fundamentally different results in the form of statistical scoring.

The previous reports also have left gaps in our knowledge. For example, there has been no published assessment of thresholds for scoring schemes more sophisticated than percentage identity. Thus, the widely discussed statistical scoring measures have never actually been evaluated on large databases of real proteins. Moreover, the different scoring schemes commonly in use have not been compared.

Beyond these issues, there is a more fundamental question: in an absolute sense, how well does pairwise sequence comparison work? That is, what fraction of homologous proteins can be detected using modern database searching methods?

In this work, we attempt to answer these questions and to overcome both of the fundamental difficulties that have hindered assessment of sequence comparison methodologies. First, we use the set of distant evolutionary relationships in the SCOP: Structural Classification of Proteins database (4), which is derived from structural and functional characteristics (5). The SCOP database provides a uniquely reliable set of homologs, which are known independently of sequence comparison. Second, we use an assessment method that jointly measures both sensitivity and specificity. This method allows straightforward comparison of different sequence searching procedures. Further, it can be used to aid interpretation of real database searches and thus provide optimal and reliable results.

**Previous Assessments of Sequence Comparison.** Several previous studies have examined the relative performance of different sequence comparison methods. The most encompassing analyses have been by Pearson (6, 7), who compared the three most commonly used programs. Of these, the Smith-Waterman algorithm (8) implemented in SSEARCH (3) is the oldest and slowest but the most rigorous. Modern heuristics have provided BLAST (1) the speed and convenience to make it the most popular program. Intermediate between these two is FASTA (3), which may be run in two modes offering either greater speed ( $ktup = 2$ ) or greater effectiveness ( $ktup = 1$ ). Pearson also considered different parameters for each of these programs.

To test the methods, Pearson selected two representative proteins from each of 67 protein superfamilies defined by the PIR database (9). Each was used as a query to search the database, and the matched proteins were marked as being homologous or unrelated according to their membership of PIR

The publication costs of this article were defrayed in part by page charge payment. This article must therefore be hereby marked "advertisement" in accordance with 18 U.S.C. §1734 solely to indicate this fact.

© 1998 by The National Academy of Sciences 0027-8424/98/956073-6\$2.00/0  
PNAS is available online at <http://www.pnas.org>.

Abbreviation: EPQ, errors per query.

<sup>†</sup>Present address: Department of Structural Biology, Stanford University, Fairchild Building D-109, Stanford, CA 94305-5126

<sup>‡</sup>To whom reprints requests should be addressed. e-mail: [brenner@hyper.stanford.edu](mailto:brenner@hyper.stanford.edu).

superfamilies. Pearson found that modern matrices and "in-scaling" of raw scores improve results considerably. He also reported that the rigorous Smith-Waterman algorithm worked slightly better than FASTA, which was in turn more effective than BLAST.

Very large scale analyses of matrices have been performed (10), and Henikoff and Henikoff (11) also evaluated the effectiveness of BLAST and FASTA. Their test with BLAST considered the ability to detect homologs above a predetermined score but had no penalty for methods which also reported large numbers of spurious matches. The Henikoffs searched the SWISS-PROT database (12) and used PROSITE (13) to define homologous families. Their results showed that the BLOSUM62 matrix (14) performed markedly better than the extrapolated PAM-series matrices (15), which previously had been popular.

A crucial aspect of any assessment is the data that are used to test the ability of the program to find homologs. But in Pearson's and the Henikoffs' evaluations of sequence comparison, the correct results were effectively unknown. This is because the superfamilies in PIR and PROSITE are principally created by using the same sequence comparison methods which are being evaluated. Interdependency of data and methods creates a "chicken and egg" problem, and means for example, that new methods would be penalized for correctly identifying homologs missed by older programs. For instance, immunoglobulin variable and constant domains are clearly homologous, but PIR places them in different superfamilies. The problem is widespread: each superfamily in PIR 48.00 with a structural homolog is itself homologous to an average of 1.6 other PIR superfamilies (16).

To surmount these sorts of difficulties, Sander and Schneider (17) used protein structures to evaluate sequence comparison. Rather than comparing different sequence comparison algorithms, their work focused on determining a length-dependent threshold of percentage identity, above which all proteins would be of similar structure. A result of this analysis was the HSP equation; it states that proteins with 25% identity over 80 residues will have similar structures, whereas shorter alignments require higher identity. (Other studies also have used structures (18–20), but these focused on a small number of model proteins and were principally oriented toward evaluating alignment accuracy rather than homology detection.)

A general solution to the problem of scoring comes from statistical measures (i.e., E-values and P-values) based on the extreme value distribution (21). Extreme value scoring was implemented analytically in the BLAST program using the Karlin and Altschul statistics (22, 23) and empirical approaches have been recently added to FASTA and SSEARCH. In addition to being heralded as a reliable means of recognizing significantly similar proteins (24, 25), the mathematical tractability of statistical scores "is a crucial feature of the BLAST algorithm" (1). The validity of this scoring procedure has been tested analytically and empirically (see ref. 2 and references in ref. 24). However, all large empirical tests used random sequences that may lack the subtle structure found within biological sequences (26, 27) and obviously do not contain any real homologs. Thus, although many researchers have suggested that statistical scores be used to rank matches (24, 25, 28), there have been no large rigorous experiments on biological data to determine the degree to which such rankings are superior.

**A Database for Testing Homology Detection.** Since the discovery that the structures of hemoglobin and myoglobin are very similar though their sequences are not (29), it has been apparent that comparing structures is a more powerful (if less convenient) way to recognize distant evolutionary relationships than comparing sequences. If two proteins show a high degree of similarity in their structural details and function, it

is very probable that they have an evolutionary relationship though their sequence similarity may be low.

The recent growth of protein structure information combined with the comprehensive evolutionary classification in the SCOP database (4, 5) have allowed us to overcome previous limitations. With these data, we can evaluate the performance of sequence comparison methods on real protein sequences whose relationships are known confidently. The SCOP database uses structural information to recognize distant homologs, the large majority of which can be determined unambiguously. These superfamilies, such as the globins or the immunoglobulins, would be recognized as related by the vast majority of the biological community despite the lack of high sequence similarity.

From SCOP, we extracted the sequences of domains of proteins in the Protein Data Bank (PDB) (30) and created two databases. One (PDB90D-B) has domains, which were all <90% identical to any other, whereas (PDB40D-B) had those <40% identical. The databases were created by first sorting all protein domains in SCOP by their quality and making a list. The highest quality domain was selected for inclusion in the database and removed from the list. Also removed from the list (and discarded) were all other domains above the threshold level of identity to the selected domain. This process was repeated until the list was empty. The PDB40D-B database contains 1,323 domains, which have 9,044 ordered pairs of distant relationships, or  $\approx 0.5\%$  of the total 1,749,006 ordered pairs. In PDB90D-B, the 2,079 domains have 53,988 relationships, representing 1.2% of all pairs. Low complexity regions of sequence can achieve spurious high scores, so these were masked in both databases by processing with the SEG program (27) using recommended parameters: 12 1.8 2.0. The databases used in this paper are available from <http://sss.stanford.edu/sss/>, and databases derived from the current version of SCOP may be found at <http://scop.mrc-lmb.cam.ac.uk/scop/>.

Analyses from both databases were generally consistent, but PDB40D-B focuses on distantly related proteins and reduces the heavy overrepresentation in the PDB of a small number of families (31, 32), whereas PDB90D-B (with more sequences) improves evaluations of statistics. Except where noted otherwise, the distant homolog results here are from PDB40D-B. Although the precise numbers reported here are specific to the structural domain databases used, we expect the trends to be general.

**Assessment Data and Procedure.** Our assessment of sequence comparison may be divided into four different major categories of tests. First, using just a single sequence comparison algorithm at a time, we evaluated the effectiveness of different scoring schemes. Second, we assessed the reliability of scoring procedures, including an evaluation of the validity of statistical scoring. Third, we compared sequence comparison algorithms (using the optimal scoring scheme) to determine their relative performance. Fourth, we examined the distribution of homologs and considered the power of pairwise sequence comparison to recognize them. All of the analyses used the databases of structurally identified homologs and a new assessment criterion.

The analyses tested BLAST (1), version 1.4.9MP, and WU-BLAST2 (2), version 2.0a13MP. Also assessed was the FASTA package, version 3.0t76 (3), which provided FASTA and the SSEARCH implementation of Smith-Waterman (8). For SSEARCH and FASTA, we used BLOSUM45 with gap penalties  $-12/-1$  (7, 16). The default parameters and matrix (BLOSUM62) were used for BLAST and WU-BLAST2.

**The "Coverage Vs. Error" Plot.** To test a particular protocol (comprising a program and scoring scheme), each sequence from the database was used as a query to search the database. This yielded ordered pairs of query and target sequences with associated scores, which were sorted, on the basis of their scores, from best to worst. The ideal method would have

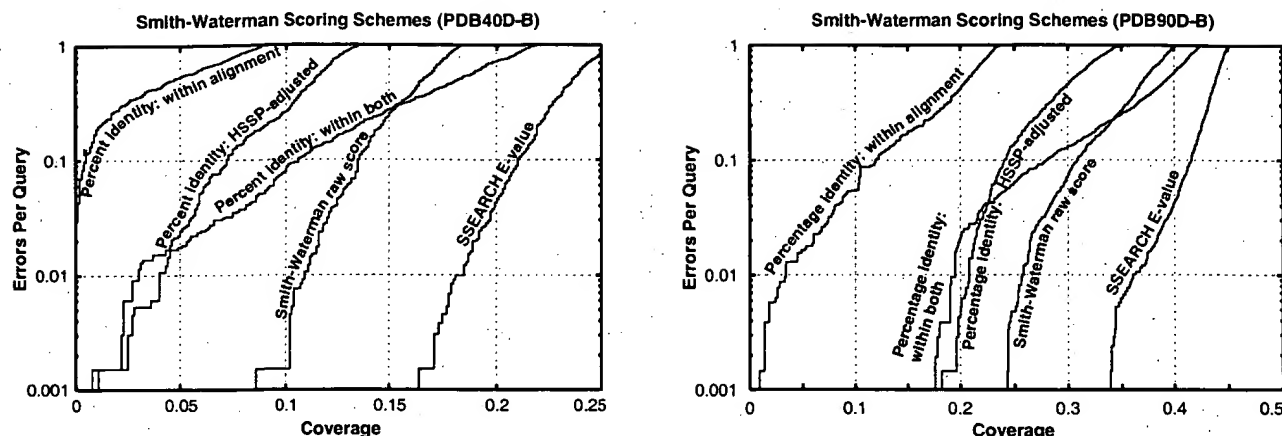


FIG. 1. Coverage vs. error plots of different scoring schemes for SSEARCH Smith-Waterman. (A) Analysis of PDB40D-B database. (B) Analysis of PDB90D-B database. All of the proteins in the database were compared with each other using the SSEARCH program. The results of this single set of comparisons were considered using five different scoring schemes and assessed. The graphs show the coverage and errors per query (EPQ) for statistical scores, raw scores, and three measures using percentage identity. In the coverage vs. error plot, the x axis indicates the fraction of all homologs in the database (known from structure) which have been detected. Precisely, it is the number of detected pairs of proteins with the same fold divided by the total number of pairs from a common superfamily. PDB40D-B contains a total of 9,044 homologs, so a score of 10% indicates identification of 904 relationships. The y axis reports the number of EPQ. Because there are 1,323 queries made in the PDB40D-B all-vs.-all comparison, 13 errors corresponds to 0.01, or 1% EPQ. The y axis is presented on a log scale to show results over the widely varying degrees of accuracy which may be desired. The scores that correspond to the levels of EPQ and coverage are shown in Fig. 4 and Table 1. The graph demonstrates the trade-off between sensitivity and selectivity. As more homologs are found (moving to the right), more errors are made (moving up). The ideal method would be in the lower right corner of the graph, which corresponds to identifying many evolutionary relationships without selecting unrelated proteins. Three measures of percentage identity are plotted. Percentage identity within alignment is the degree of identity within the aligned region of the proteins, without consideration of the alignment length. Percentage identity within both is the number of identical residues in the aligned region as a percentage of the average length of the query and target proteins. The HSP equation (17) is  $H = 290.15l^{-0.562}$  where  $l$  is length for  $10 < l < 80$ ;  $H > 100$  for  $l < 10$ ;  $H = 24.7$  for  $l > 80$ . The percentage identity HSP-adjusted score is the percent identity within the alignment minus  $H$ . Smith-Waterman raw scores and E-values were taken directly from the sequence comparison program.

perfect separation, with all of the homologs at the top of the list and unrelated proteins below. In practice, perfect separation is impossible to achieve so instead one is interested in drawing a threshold above which there are the largest number of related pairs of sequences consistent with an acceptable error rate.

Our procedure involved measuring the coverage and error for every threshold. Coverage was defined as the fraction of structurally determined homologs that have scores above the selected threshold; this reflects the sensitivity of a method. Errors per query (EPQ), an indicator of selectivity, is the number of nonhomologous pairs above the threshold divided by the number of queries. Graphs of these data, called coverage vs. error plots, were devised to understand how

protocols compare at different levels of accuracy. These graphs share effectively all of the beneficial features of Receiver Operating Characteristic (ROC) plots (33, 34) but better represent the high degrees of accuracy required in sequence comparison and the huge background of nonhomologs.

This assessment procedure is directly relevant to practical sequence database searching, for it provides precisely the information necessary to perform a reliable sequence database search. The EPQ measure places a premium on score consistency; that is, it requires scores to be comparable for different queries. Consistency is an aspect which has been largely

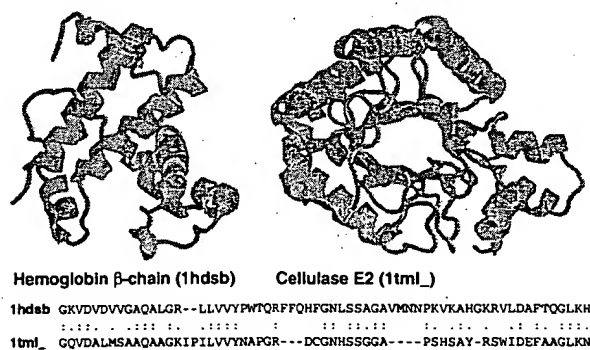


FIG. 2. Unrelated proteins with high percentage identity. Hemoglobin  $\beta$ -chain (PDB code 1hds chain b, ref. 38, Left) and cellulase E2 (PDB code 1tml, ref. 39, Right) have 39% identity over 64 residues, a level which is often believed to be indicative of homology. Despite this high degree of identity, their structures strongly suggest that these proteins are not related. Appropriately, neither the raw alignment score of 85 nor the E-value of 1.3 is significant. Proteins rendered by RASMOL (40).

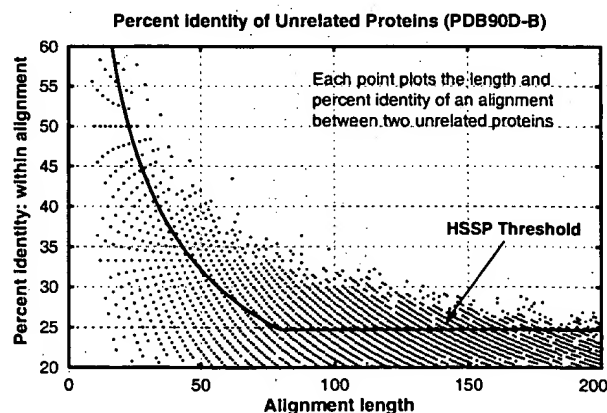


FIG. 3. Length and percentage identity of alignments of unrelated proteins in PDB90D-B: Each pair of nonhomologous proteins found with SSEARCH is plotted as a point whose position indicates the length and the percentage identity within the alignment. Because alignment length and percentage identity are quantized, many pairs of proteins may have exactly the same alignment length and percentage identity. The line shows the HSP threshold (though it is intended to be applied with a different matrix and parameters).



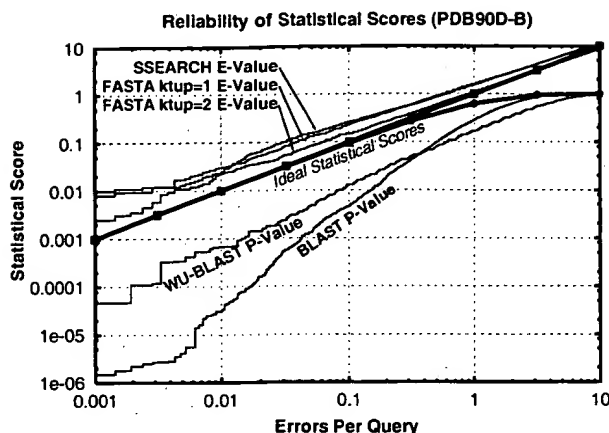


FIG. 4. Reliability of statistical scores in PDB90D-B: Each line shows the relationship between reported statistical score and actual error rate for a different program. E-values are reported for SSEARCH and FASTA, whereas P-values are shown for BLAST and WU-BLAST2. If the scoring were perfect, then the number of errors per query and the E-values would be the same, as indicated by the upper bold line. (P-values should be the same as EPQ for small numbers, and diverges at higher values, as indicated by the lower bold line.) E-values from SSEARCH and FASTA are shown to have good agreement with EPQ but underestimate the significance slightly. BLAST and WU-BLAST2 are overconfident, with the degree of exaggeration dependent upon the score. The results for PDB40D-B were similar to those for PDB90D-B despite the difference in number of homologs detected. This graph could be used to roughly calibrate the reliability of a given statistical score.

ignored in previous tests but is essential for the straightforward or automatic interpretation of sequence comparison results. Further, it provides a clear indication of the confidence that should be ascribed to each match. Indeed, the EPQ measure should approximate the expectation value reported by database searching programs, if the programs' estimates are accurate.

**The Performance of Scoring Schemes.** All of the programs tested could provide three fundamental types of scores. The first score is the percentage identity, which may be computed in several ways based on either the length of the alignment or the lengths of the sequences. The second is a "raw" or "Smith-Waterman" score, which is the measure optimized by the Smith-Waterman algorithm and is computed by summing the substitution matrix scores for each position in the alignment and subtracting gap penalties. In BLAST, a measure

related to this score is scaled into bits. Third is a statistical score based on the extreme value distribution. These results are summarized in Fig. 1.

**Sequence Identity.** Though it has been long established that percentage identity is a poor measure (35), there is a common rule-of-thumb stating that 30% identity signifies homology. Moreover, publications have indicated that 25% identity can be used as a threshold (17, 36). We find that these thresholds, originally derived years ago, are not supported by present results. As databases have grown, so have the possibilities for chance alignments with high identity; thus, the reported cutoffs lead to frequent errors. Fig. 2 shows one of the many pairs of proteins with very different structures that nonetheless have high levels of identity over considerable aligned regions. Despite the high identity, the raw and the statistical scores for such incorrect matches are typically not significant. The principal reasons percentage identity does so poorly seem to be that it ignores information about gaps and about the conservative or radical nature of residue substitutions.

From the PDB90D-B analysis in Fig. 3, we learn that 30% identity is a reliable threshold for this database only for sequence alignments of at least 150 residues. Because one unrelated pair of proteins has 43.5% identity over 62 residues, it is probably necessary for alignments to be at least 70 residues in length before 40% is a reasonable threshold, for a database of this particular size and composition.

At a given reliability, scores based on percentage identity detect just a fraction of the distant homologs found by statistical scoring. If one measures the percentage identity in the aligned regions without consideration of alignment length, then a negligible number of distant homologs are detected. Use of the HSP equation improves the value of percentage identity, but even this measure can find only 4% of all known homologs at 1% EPQ. In short, percentage identity discards most of the information measured in a sequence comparison.

**Raw Scores.** Smith-Waterman raw scores perform better than percentage identity (Fig. 1), but ln-scaling (7) provided no notable benefit in our analysis. It is necessary to be very precise when using either raw or bit scores because a 20% change in cutoff score could yield a tenfold difference in EPQ. However, it is difficult to choose appropriate thresholds because the reliability of a bit score depends on the lengths of the proteins matched and the size of the database. Raw score thresholds also are affected by matrix and gap parameters.

**Statistical Scores.** Statistical scores were introduced partly to overcome the problems that arise from raw scores. This scoring scheme provides the best discrimination between homologous proteins and those which are unrelated. Most

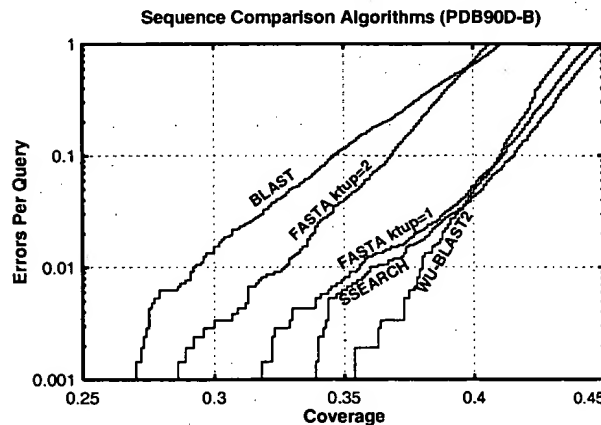
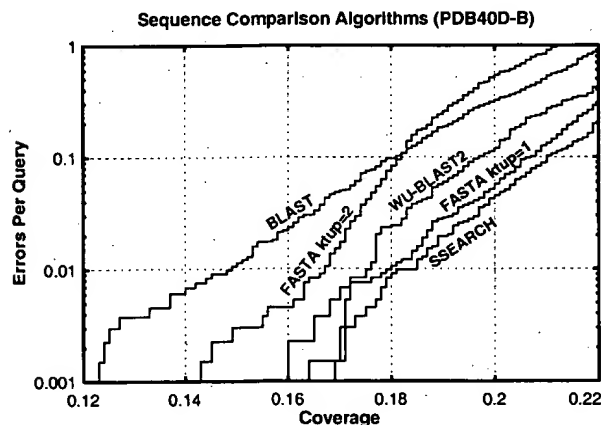


FIG. 5. Coverage vs. error plots of different sequence comparison methods: Five different sequence comparison methods are evaluated, each using statistical scores (E- or P-values). (A) PDB40D-B database. In this analysis, the best method is the slow SSEARCH, which finds 18% of relationships at 1% EPQ. FASTA ktup = 1 and WU-BLAST2 are almost as good. (B) PDB90D-B database. The quick WU-BLAST2 program provides the best coverage at 1% EPQ on this database, although at higher levels of error it becomes slightly worse than FASTA ktup = 1 and SSEARCH.



likely, its power can be attributed to its incorporation of more information than any other measure; it takes account of the full substitution and gap data (like raw scores) but also has details about the sequence lengths and composition and is scaled appropriately.

We find that statistical scores are not only powerful, but also easy to interpret. SSEARCH and FASTA show close agreement between statistical scores and actual number of errors per query (Fig. 4). The expectation value score gives a good, slightly conservative estimate of the chances of the two sequences being found at random in a given query. Thus, an E-value of 0.01 indicates that roughly one pair of nonhomologs of this similarity should be found in every 100 different queries. Neither raw scores nor percentage identity can be interpreted in this way, and these results validate the suitability of the extreme value distribution for describing the scores from a database search.

The P-values from BLAST also should be directly interpretable but were found to overstate significance by more than two orders of magnitude for 1% EPQ for this database. Nonetheless, these results strongly suggest that the analytic theory is fundamentally appropriate. WU-BLAST2 scores were more reliable than those from BLAST, but also exaggerate expected confidence by more than an order of magnitude at 1% EPQ.

**Overall Detection of Homologs and Comparison of Algorithms.** The results in Fig. 5A and Table 1 show that pairwise sequence comparison is capable of identifying only a small fraction of the homologous pairs of sequences in PDB40D-B. Even SSEARCH with E-values, the best protocol tested, could find only 18% of all relationships at a 1% EPQ. BLAST, which identifies 15%, was the worst performer, whereas FASTA  $k_{\text{tup}} = 1$  is nearly as effective as SSEARCH. FASTA  $k_{\text{tup}} = 2$  and WU-BLAST2 are intermediate in their ability to detect homologs. Comparison of different algorithms indicates that those capable of identifying more homologs are generally slower. SSEARCH is 25 times slower than BLAST and 6.5 times slower than FASTA  $k_{\text{tup}} = 1$ . WU-BLAST2 is slightly faster than FASTA  $k_{\text{tup}} = 2$ , but the latter has more interpretable scores.

In PDB90D-B, where there are many close relationships, the best method can identify only 38% of structurally known homologs (Fig. 5B). The method which finds that many relationships is WU-BLAST2. Consequently, we infer that the differences between FASTA  $k_{\text{tup}} = 1$ , SSEARCH, and WU-BLAST2 programs are unlikely to be significant when compared with variation in database composition and scoring reliability.

Fig. 6 helps to explain why most distant homologs cannot be found by sequence comparison: a great many such relationships have no more sequence identity than would be expected by chance. SSEARCH with E-values can recognize >90% of the homologous pairs with 30–40% identity. In this region, there are 30 pairs of homologous proteins that do not have significant E-values, but 26 of these involve sequences with <50 residues. Of sequences having 25–30% identity, 75% are identified by SSEARCH E-values. However, although the number of homologs grows at lower levels of identity, the detection falls off sharply: only 40% of homologs with 20–25% identity

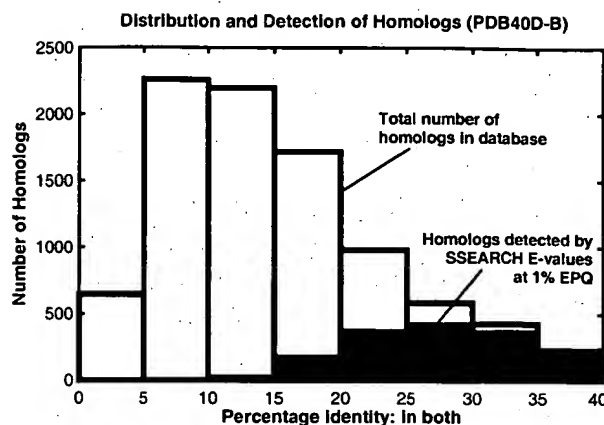


FIG. 6. Distribution and detection of homologs in PDB40D-B. Bars show the distribution of homologous pairs PDB40D-B according to their identity (using the measure of identity in both). Filled regions indicate the number of these pairs found by the best database searching method (SSEARCH with E-values) at 1% EPQ. The PDB40D-B database contains proteins with <40% identity, and as shown on this graph, most structurally identified homologs in the database have diverged extremely far in sequence and have <20% identity. Note that the alignments may be inaccurate, especially at low levels of identity. Filled regions show that SSEARCH can identify most relationships that have 25% or more identity, but its detection wanes sharply below 25%. Consequently, the great sequence divergence of most structurally identified evolutionary relationships effectively defeats the ability of pairwise sequence comparison to detect them.

are detected and only 10% of those with 15–20% can be found. These results show that statistical scores can find related proteins whose identity is remarkably low; however, the power of the method is restricted by the great divergence of many protein sequences.

After completion of this work, a new version of pairwise BLAST was released: BLASTGP (37). It supports gapped alignments, like WU-BLAST2, and dispenses with sum statistics. Our initial tests on BLASTGP using default parameters show that its E-values are reliable and that its overall detection of homologs was substantially better than that of ungapped BLAST, but not quite equal to that of WU-BLAST2.

## CONCLUSION

The general consensus amongst experts (see refs. 7, 24, 25, 27 and references therein) suggests that the most effective sequence searches are made by (i) using a large current database in which the protein sequences have been complexity masked and (ii) using statistical scores to interpret the results. Our experiments fully support this view.

Our results also suggest two further points. First, the E-values reported by FASTA and SSEARCH give fairly accurate estimates of the significance of each match, but the P-values provided by BLAST and WU-BLAST2 underestimate the true

Table 1. Summary of sequence comparison methods with PDB40D-B

Method	Relative Time*	1% EPQ Cutoff	Coverage at 1% EPQ
SSEARCH % identity: within alignment	25.5	>70%	<0.1
SSEARCH % identity: within both	25.5	34%	3.0
SSEARCH % identity: HSSP-scaled	25.5	35% (HSSP + 9.8)	4.0
SSEARCH Smith-Waterman raw scores	25.5	142	10.5
SSEARCH E-values	25.5	0.03	18.4
FASTA $k_{\text{tup}} = 1$ E-values	3.9	0.03	17.9
FASTA $k_{\text{tup}} = 2$ E-values	1.4	0.03	16.7
WU-BLAST2 P-values	1.1	0.003	17.5
BLAST P-values	1.0	0.00016	14.8

\*Times are from large database searches with genome proteins.

extent of errors. Second, SSEARCH, WU-BLAST2, and FASTA ktup = 1 perform best, though BLAST and FASTA ktup = 2 detect most of the relationships found by the best procedures and are appropriate for rapid initial searches.

The homologous proteins that are found by sequence comparison can be distinguished with high reliability from the huge number of unrelated pairs. However, even the best database searching procedures tested fail to find the large majority of distant evolutionary relationships at an acceptable error rate. Thus, if the procedures assessed here fail to find a reliable match, it does not imply that the sequence is unique; rather, it indicates that any relatives it might have are distant ones.\*\*

\*\*Additional and updated information about this work, including supplementary figures, may be found at <http://sss.stanford.edu/sss/>.

The authors are grateful to Drs. A. G. Murzin, M. Levitt, S. R. Eddy, and G. Mitchison for valuable discussion. S.E.B. was principally supported by a St. John's College (Cambridge, UK) Benefactors' Scholarship and by the American Friends of Cambridge University. S.E.B. dedicates his contribution to the memory of Rabbi Albert T. and Clara S. Bilgray.

- Altschul, S. F., Gish, W., Miller, W., Myers, E. W. & Lipman, D. J. (1990) *J. Mol. Biol.* **215**, 403–410.
- Altschul, S. F. & Gish, W. (1996) *Methods Enzymol.* **266**, 460–480.
- Pearson, W. R. & Lipman, D. J. (1988) *Proc. Natl. Acad. Sci. USA* **85**, 2444–2448.
- Murzin, A. G., Brenner, S. E., Hubbard, T. & Chothia, C. (1995) *J. Mol. Biol.* **247**, 536–540.
- Brenner, S. E., Chothia, C., Hubbard, T. J. P. & Murzin, A. G. (1996) *Methods Enzymol.* **266**, 635–643.
- Pearson, W. R. (1991) *Genomics* **11**, 635–650.
- Pearson, W. R. (1995) *Protein Sci.* **4**, 1145–1160.
- Smith, T. F. & Waterman, M. S. (1981) *J. Mol. Biol.* **147**, 195–197.
- George, D. G., Hunt, L. T. & Barker, W. C. (1996) *Methods Enzymol.* **266**, 41–59.
- Vogt, G., Etzold, T. & Argos, P. (1995) *J. Mol. Biol.* **249**, 816–831.
- Henikoff, S. & Henikoff, J. G. (1993) *Proteins* **17**, 49–61.
- Bairoch, A. & Apweiler, R. (1996) *Nucleic Acids Res.* **24**, 21–25.
- Bairoch, A., Bucher, P. & Hofmann, K. (1996) *Nucleic Acids Res.* **24**, 189–196.
- Henikoff, S. & Henikoff, J. G. (1992) *Proc. Natl. Acad. Sci. USA* **89**, 10915–10919.
- Dayhoff, M., Schwartz, R. M. & Orcutt, B. C. (1978) in *Atlas of Protein Sequence and Structure*, ed. Dayhoff, M. (National Bio-medical Research Foundation, Silver Spring, MD), Vol. 5, Suppl. 3, pp. 345–352.
- Brenner, S. E. (1996) Ph.D. thesis. (University of Cambridge, UK).
- Sander, C. & Schneider, R. (1991) *Proteins* **9**, 56–68.
- Johnson, M. S. & Overington, J. P. (1993) *J. Mol. Biol.* **233**, 716–738.
- Barton, G. J. & Sternberg, M. J. E. (1987) *Protein Eng.* **1**, 89–94.
- Lesk, A. M., Levitt, M. & Chothia, C. (1986) *Protein Eng.* **1**, 77–78.
- Arratia, R., Gordon, L. & M, W. (1986) *Ann. Stat.* **14**, 971–993.
- Karlin, S. & Altschul, S. F. (1990) *Proc. Natl. Acad. Sci. USA* **87**, 2264–2268.
- Karlin, S. & Altschul, S. F. (1993) *Proc. Natl. Acad. Sci. USA* **90**, 5873–5877.
- Altschul, S. F., Boguski, M. S., Gish, W. & Wootton, J. C. (1994) *Nat. Genet.* **6**, 119–129.
- Pearson, W. R. (1996) *Methods Enzymol.* **266**, 227–258.
- Lipman, D. J., Wilbur, W. J., Smith, T. F. & Waterman, M. S. (1984) *Nucleic Acids Res.* **12**, 215–226.
- Wootton, J. C. & Federhen, S. (1996) *Methods Enzymol.* **266**, 554–571.
- Waterman, M. S. & Vingron, M. (1994) *Stat. Science* **9**, 367–381.
- Perutz, M. F., Kendrew, J. C. & Watson, H. C. (1965) *J. Mol. Biol.* **13**, 669–678.
- Abola, E. E., Bernstein, F. C., Bryant, S. H., Koetzle, T. F. & Weng, J. (1987) in *Crystallographic Databases: Information Content, Software Systems, Scientific Applications*, eds. Allen, F. H., Bergerhoff, G. & Sievers, R. (Data Comm. Intl. Union Crystallogr., Cambridge, UK), pp. 107–132.
- Brenner, S. E., Chothia, C. & Hubbard, T. J. P. (1997) *Curr. Opin. Struct. Biol.* **7**, 369–376.
- Orengo, C., Michie, A., Jones, S., Jones, D. T., Swindells, M. B. & Thornton, J. (1997) *Structure (London)* **5**, 1093–1108.
- Zweig, M. H. & Campbell, G. (1993) *Clin. Chem.* **39**, 561–577.
- Gribskov, M. & Robinson, N. L. (1996) *Comput. Chem.* **20**, 25–33.
- Fitch, W. M. (1966) *J. Mol. Biol.* **16**, 9–16.
- Chung, S. Y. & Subbiah, S. (1996) *Structure (London)* **4**, 1123–1127.
- Altschul, S. F., Madden, T. L., Schaffer, A. A., Zhang, J., Zhang, Z., Miller, W. & Lipman, D. J. (1997) *Nucleic Acids Res.* **25**, 3389–3402.
- Girling, R., Schmidt, W., Jr, Houston, T., Amma, E. & Huisman, T. (1979) *J. Mol. Biol.* **131**, 417–433.
- Spezio, M., Wilson, D. & Karplus, P. (1993) *Biochemistry* **32**, 9906–9916.
- Sayle, R. A. & Milner-White, E. J. (1995) *Trends Biochem. Sci.* **20**, 374–376.

- These data were digitally recorded by stand-alone units [borrowed from Incorporated Research Institutions for Seismology (IRIS), Washington, DC] arranged in arrays 25 km long with receiver intervals of 100 to 300 m.
20. Gravity was measured by a Worden (Texas Instruments, Houston, TX) gravimeter and tied to the McMurdo gravity base station. The observed gravity anomaly was found to be within 0.5 mgal of that from a previous regional survey (2). Relative elevations along the profile were measured by pairs of barometers.
  21. Holes were drilled by melting of the ice with hot water pumped under pressure. For the multichannel reflection work, 7.5-kg charges were spaced every 200 m along the profile. Two charges 1.6 km apart were detonated for each streamer location. This pattern resulted in an effective 120-channel receiving array 3 km long. The sources for the wide-angle reflection and refraction data were several explosions of 100 to 400 kg.
  22. L. R. Bartek, P. R. Vall, J. B. Anderson, P. A. Emmet, S. Wu, *J. Geophys. Res.* **96**, 8753 (1991).
  23. K. Hinz and M. Block, in *Proceedings of the 11th World Petroleum Congress* (Wiley, New York, 1984), pp. 279-291.
  24. Velocities directly beneath the sea floor were less than that of solid ice ( $3.8 \text{ km s}^{-1}$ ) and therefore produced no refracted arrivals. For this portion of the refraction model (beneath the sea floor under the ice shelf), velocities were obtained from the stacking velocities of the reflection data.
  25. A. K. Cooper and F. J. Davey, *The Antarctic Continental Margin: Geology and Geophysics of the Western Ross Sea* (Circum-Pacific Council for Energy and Mineral Resources (CPEMR), Houston, 1987).
  26. D. R. H. O'Connell and T. M. Stepp, in *Geol. Jahrb.*, in press.
  27. L. D. Hale and G. A. Thompson, *J. Geophys. Res.* **87**, 4625 (1982).
  28. R. Meisner and N. J. Kusznir, *Ann. Geophys. Ser. B* **5**, 365 (1987).
  29. B. S. Gibson and A. R. Levander, *Geophys. Res. Lett.* **15**, 617 (1988).
  30. W. A. Heiskanen and F. A. Vening Meinesz, *The Earth and Its Gravity Field* (McGraw-Hill, New York, 1958).
  31. J. Braun and C. Beaumont, *Geology* **17**, 760 (1989).
  32. R. S. Stein, G. C. P. King, J. B. Rundle, *J. Geophys. Res.* **93**, 13319 (1988).
  33. M. H. P. Bott and T. A. Stern, *Tectonophysics* **201**, 341 (1992).
  34. R. I. Kalamardes, J. H. Berg, R. A. Hank, *Science* **237**, 1192 (1987).
  35. E. B. Goodwin and J. McCarthy, *J. Geophys. Res.* **95**, 20097 (1990).
  36. W. R. Buck, *Earth Planet. Sci. Lett.* **77**, 362 (1986).
  37. P. J. Barrett, M. J. Hambrey, D. M. Harwood, A. R. Pyne, P.-N. Webb, *DSIR Bull.* **245**, 241 (1989).
  38. C. M. Clapperton and D. E. Sugden, *Quat. Sci. Rev.* **9**, 253 (1990).
  39. A. C. Johnston, *Nature* **330**, 467 (1987).
  40. G. Zandt and G. Owens, *Bull. Seismol. Soc. Am.* **70**, 1501 (1980).
  41. P. Wallman and R. J. Tingey, *Nature* **291**, 142 (1981).
  42. The stacked profile was enhanced by the combination of four adjacent traces and the application of a two-dimensional median filter and was not migrated.
  43. The BSR here shares similar characteristics with BSRs identified and drilled in low-latitude margins: It simulates the sea floor, cuts across stratigraphic units, exhibits a polarity reversal of the wavelet compared to the sea floor, and is overlain by an acoustically opaque layer. Bottom-simulating reflectors are caused by a thin layer of free gas at the base of a gas hydrate-cemented layer. Methane gas has been encountered in drill holes and cores around Antarctica, but despite the anomalously large depth of the Antarctic shelves, BSRs have rarely been documented [K. A. Kvernøden, M. Golan-Bac, J. B. Rapp, in *The Antarctic Continental Margin: Geology and Geophysics of Offshore Wilkes*

Land, S. L. Ettreim and M. A. Hampton, Eds. (CPEMR, Houston, 1987), pp. 205-213].

44. We modeled the refraction data using both forward- and inverse-ray tracing programs [J. H. Luetgert, *U.S. Geol. Surv. Open-File Rep.* **88-238** (1988), p. 52; W. J. Lutter, R. L. Nowack, L. W. Bräile, *J. Geophys. Res.* **95**, 4821 (1990)]. Values for ice thickness and absolute elevation from previous regional surveys of the Ross Ice Shelf [D. G. Albert and C. R. Bentley, in *The Ross Ice Shelf: Glaciology and Geophysics*, C. R. Bentley and D. E. Hayes, Eds. (American Geophysical Union, Washington, DC, 1990), pp. 87-108] were used for modeling of the refraction and gravity data.
45. We thank R. Busby, B. Harris, S. Heaphy, T. Hefford,

C. Hobbs, N. Lord, D. Lousley, and B. Straite for their invaluable help in the field; Polar Ice Coring Office, (University of Alaska, Fairbanks) for drilling the shot holes; A. Melhuish, M. Lee, W. Agana, W. Poag, W. Dillon, and J. Zwinakis for helping with processing, interpretation, and drafting; P. Barrett, C. Bentley, F. Davey, D. Hutchinson, K. Klitgord, G. Thompson, and one anonymous individual for helpful reviews; Norsk-Hydro, Y. Kristoffersen, and E. Rygg for lending the snow streamer; Grant-Norpac (Houston, TX) for lending computer boards; and IRIS for sending a technician and lending stand-alone recording units and peripherals. Funded by National Science Foundation grant DPP89-17834 and the New Zealand Science Foundation.

## RESEARCH ARTICLES

# Three-Dimensional Structure of Myosin Subfragment-1: A Molecular Motor

Ivan Rayment,\* Wojciech R. Rypniewski,† Karen Schmidt-Bäse,‡ Robert Smith, Diana R. Tomchick,§ Matthew M. Benning, Donald A. Winkelmann, Gary Wesenberg, Hazel M. Holden

Directed movement is a characteristic of many living organisms and occurs as a result of the transformation of chemical energy into mechanical energy. Myosin is one of three families of molecular motors that are responsible for cellular motility. The three-dimensional structure of the head portion of myosin, or subfragment-1, which contains both the actin and nucleotide binding sites, is described. This structure of a molecular motor was determined by single crystal x-ray diffraction. The data provide a structural framework for understanding the molecular basis of motility.

Motility is one of the characteristic features of many living organisms and involves the transduction of chemical into mechanical energy. Only a limited number of strategies have evolved to accomplish this task. At present, three major classes of molecular motors have been identified, myosin, dynein, and kinesin, and all are important in cellular movement (1). Of these three proteins, the most abundant is myosin, which plays both a structural and an enzymatic role in both muscle contraction and intracellular motility.

I. Rayment, W. R. Rypniewski, K. Schmidt-Bäse, R. Smith, D. R. Tomchick, M. M. Benning, G. Wesenberg, and H. M. Holden are in the Department of Biochemistry and Institute for Enzyme Research, University of Wisconsin, 1710 University Avenue, Madison, WI 53705. D. A. Winkelmann is in the Department of Pathology, Robert Wood Johnson Medical School, Piscataway, NJ 08854.

\*To whom all correspondence should be addressed.

†Present address: European Molecular Biology Laboratory, Notkestrasse 85, 2000 Hamburg 52, Germany.

‡Present address: Max Planck Institute for Biochemistry, 8033 Martinsried, Germany.

§Present address: Department of Biological Sciences, Purdue University, West Lafayette, IN 47907.

The role of myosin in movement has been most clearly defined from the study of cross-striated skeletal muscle, which shows a high degree of structural organization. In striated muscle the basic contractile unit is the sarcomere, which consists of overlapping arrays of thick and thin filaments. During contraction, these filaments, which are composed primarily of myosin and actin, respectively, slide past one another, thereby shortening the length of the sarcomere (2). Electron micrographs of muscle in rigor have revealed connections between the filaments in the overlap region, the so-called crossbridges. These crossbridges are formed by the globular regions of the myosin molecule and are responsible for force generation in the contractile process through the hydrolysis of adenosine triphosphate (ATP).

Myosin, which has a molecular size of about 520 kilodaltons, consists of two 220-kD heavy chains and two pairs of light chains that vary in molecular size depending on the source but are usually between 15 and 22 kD (3, 4). The molecule is highly

asymmetric, consisting of two globular heads attached to a long tail. Each heavy chain forms the bulk of one head and intertwines with its neighbor to form the tail. Limited proteolytic digestion has shown that the myosin head, or subfragment-1 (S1), contains an ATP, actin, and two light chain binding sites and that the myosin rod, which is formed by a coiled coil of two  $\alpha$  helices, accounts for the self-association of myosin at low ionic strength and the formation of the thick filament backbone (3). Spudich and co-workers have demonstrated that the globular head portions of myosin are sufficient to generate movement of actin in an *in vitro* motility assay (5).

Each globular head, derived from limited proteolysis, consists of a heavy chain fragment having a molecular size of 95 kD and two light chains yielding a combined molecular size of ~130 kD (6). The two light chains differ in their structure and properties and are known by a variety of names. In this article they are referred to as the regulatory and essential light chains. Neither type is required for the adenosine triphosphatase (ATPase) activity of the head (7). In some species, however, these chains regulate or modulate the ATPase activity of myosin in the presence of actin (8, 9). Amino acid sequence analyses reveal that both light chains share considerable sequence similarity with calmodulin and troponin C although most of the divalent cation binding sites have been lost during evolution (10).

During the last 40 years, enormous effort has been expended toward understanding the structure and function of the myosin head (11). Measurements from electron micrographs have suggested that the myosin head is pear-shaped, about 190 Å long and 50 Å wide at its thickest point (12). Molecular dimensions subsequently derived from studies of fixed thin sections cut from crystals of myosin S1 were consistent with these observations (13).

Although much biochemical and physical information has accumulated for myosin since 1950, structural knowledge of this protein or any other molecular motor has been lacking. We now describe the tertiary structure of the myosin head and suggest how this protein may serve to transduce energy from the hydrolysis of ATP into directed movement. We present the three-dimensional structure of myosin S1 at a nominal resolution of 2.8 Å and refinement R factor of 22.3 percent for all x-ray data recorded in that range.

**Crystallization of myosin subfragment-1.** Myosin is an abundant protein that can be easily prepared in gram quantities. Likewise, the myosin head, which is readily cleaved from the rest of the molecule by mild prote-

olysis, can be prepared in large quantities. This soluble subfragment has been known for approximately 30 years and has resisted crystallization despite numerous attempts. In view of its central importance for understanding the molecular basis of muscle contraction, we undertook an alternative approach to the usual ways of obtaining x-ray quality crystals. The protein was first subjected to mild chemical modification of the lysine residues by reductive methylation. This chemical modification has long been used as a gentle way to introduce a radioactive label into a protein (14).

Considerable effort was expended to determine the optimal procedure for modifying the protein since it was recognized that complete, homogeneous modification of the molecule was essential for obtaining high-quality crystals (Table 1). Many of the experiments necessary to derive the optimal protocol for methylation were performed in a parallel study on hen egg white lysozyme (15). In that study the three-dimensional structure of the modified protein was determined and refined to 1.8 Å resolution and shown to be essentially identical to that of the native protein except for the modified lysine residues. Modification of the lysine residues in

lysozyme dramatically changed its crystallization properties. The kinetic and structural effects of this treatment on myosin S1 are discussed below.

Myosin isolated from chicken pectoralis muscle consists of a mixed population of two isozymes caused by the existence of two species of the essential light chain (16). These light chains are referred to as A1 (21 kD) and A2 (16 kD). Amino acid sequence studies of the light chains have demonstrated that A1 and A2 are identical over their 142 residues at the COOH-terminus. The size difference is caused by an additional 41 amino acids present at the NH<sub>2</sub>-terminus of A1. These isozymes arise by alternative transcription and two modes of splicing from a single gene (17).

The crystals used in our study contained both isoforms of the essential light chain. Myosin S1 was prepared by digestion with papain in the presence of MgCl<sub>2</sub> because the fragment produced under these conditions contained both the regulatory and essential light chains. The major drawback of papain as a proteolytic enzyme, however, was its lack of specificity. Apart from cleaving the heavy chain at the head-rod junction, additional proteolytic breaks were introduced into both the regulatory and A1 essential light chains. Also, there was partial phosphorylation of the regulatory light chain by endogenous myosin light chain kinase. The myosin S1 was prepared by an improved purification protocol that removed the heterogeneity arising from both proteolysis of the light chains and phosphorylation of the regulatory light chain (18).

Crystals were grown by batch methods from 1.35 M ammonium sulfate, 500 mM potassium chloride, and 50 mM potassium phosphate (pH 6.7) in the presence of 5 mM dithiothreitol and 0.5 mM sodium azide at a final protein concentration of 8 to 12 mg/ml. Crystallization was initiated by microseeding, and the crystals grew as thick rods to a length of 1 to 2 mm and a width and thickness of 0.4 and 0.3 mm, respectively, over a period of 2 to 3 months at 4°C. They belonged to the space group C222<sub>1</sub> with unit cell dimensions of  $a = 98.4$ ,  $b = 124.2$ ,  $c = 274.9$  Å, and one molecule in the asymmetric unit. These crystals were different from those originally reported (19) and arose from improvements in both the chemical modification procedure and the protein homogeneity.

**Structure determination.** The x-ray data were collected in two stages (20). First, x-ray data sets to 4.5 Å resolution for the native and heavy atom-containing crystals were recorded by an area detector with the goal of determining the positions of the metal binding sites. These data were then extended to 2.8 Å resolution with

**Table 1.** Amino acid analysis of modified and native myosin S1 (60). Prior to modification, the protein, at 5 mg/ml, was dialyzed against 200 mM potassium phosphate, pH 7.5, 1 mM MgCl<sub>2</sub>. The protein was reductively methylated at 4°C by the sequential addition of 1 M dimethylamine borane complex dissolved in water (20  $\mu$ l per milliliter of protein) and 1 M formaldehyde (40  $\mu$ l per milliliter of protein) with rapid stirring. This process was repeated after 2 hours; a further portion (10  $\mu$ l/ml) of dimethylamine borane complex was added after 2 hours and the reaction mixture was kept overnight at 4°C in the dark. The reaction was quenched by the addition of 3.8 M ammonium sulfate to a final concentration of 1 M and then dialyzed for 48 hours against 2.5 M ammonium sulfate, 50 mM potassium phosphate at pH 6.7 to precipitate the protein (15, 49). All except three to four of the lysine residues were modified. Discrepancy between the total number of lysine residues in the native and modified protein may have arisen from a calibration error in the dimethyllysine standard. The analyses for histidine, methionine, and arginine are shown as controls.

Amino acid	Residues (no.)		
	Theoretical	Native	Modified
Lysine	103	96.2	4.2
Me <sub>2</sub> -Lys	0	0	0
Me <sub>2</sub> -Lys	0	0.6	96.7
Me <sub>2</sub> -Lys	3	3.6	3.4
Total lysine	106	100.4	104.3
Histidine	24	23.7	23.2
Methionine	39	39.4	38.9
Arginine	46	47.5	47.2

synchrotron radiation at Stanford University (SSRL) and Cornell University (CHESS). We recognized early that x-ray data collection and determination of the protein phases by multiple isomorphous replacement would be difficult unless care was taken to minimize the systematic errors introduced by differences between the successive protein preparations. Consequently, for each stage in the heavy atom derivative data collection, a corresponding native data set was recorded from the same protein preparation. For each purification trial, approximately 700 mg of myosin S1 was prepared and set up for crystallization. Many attempts were made before a single preparation yielded sufficient crystals for x-ray data collection.

The structure was determined by a combination of multiple isomorphous replacement and solvent flattening. The first derivative solved was obtained from crystals soaked in trimethyllead acetate and proved to be highly isomorphous with only four binding sites (21). It was used to determine the positions of the other heavy atom binding sites by difference Fourier techniques (Table 2). The positions and occupancies of the heavy atom sites were refined according to the origin-removed Patterson-function correlation method by the program HEAVY (22). The overall figures of merit for the area detector, CHESS, and SSRL synchrotron data were 0.47, 0.58, and 0.42, respectively.

The higher resolution x-ray data collected at SSRL were placed on the same scale as the area detector data and included as a block from 4.5 to 2.8 Å. Efforts to merge the overlapping data between the area detector and synchrotron data were unsatisfactory. However, the phase information from all three sources was combined throughout the entire resolution range via the phase probability coefficients (23).

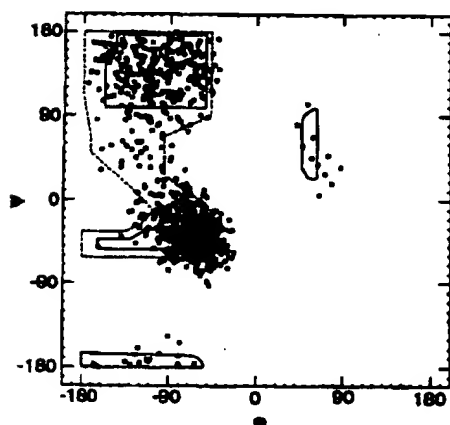


Fig. 1. Ramachandran plot of the main chain dihedral angles of all non-glycyl residues in the model presented.

These protein phases were improved by solvent flattening (24). The positions and occupancies of heavy atom binding sites were further refined against these modified phases (25). This gave an improved electron density map into which approximately 550 alanine residues were built with the program FRODO (26). The map showed good connectivity and many well-defined side chains.

Once several long segments were connected, the positions of these alanine residues were matched to the known amino acid sequence (27, 28). At this stage phase information from the partial model was combined with the heavy atom derivative phases by the program SIGMAA (29). The structure was refined concurrently with the model building process by the program package TNT (30). Once the model building was near completion, a cycle of refinement with X-PLOR (31) was performed to improve the conformations of the side chains. The strategy of alternate model

building and refining proved successful and constantly improved the estimation of the protein phases. Toward the end of the analysis there were clear segments of electron density corresponding to portions of the light chains that were completely missing in the original maps phased with heavy atom derivatives alone.

At present, 1072 residues (of a total of 1157) have been built into the electron density map. The model was refined to an *R* factor of 22.3 percent for all measured x-ray data between 30 to 2.8 Å with root-mean-square deviations from ideal geometry of 0.018 Å for bond lengths, 2.5° for bond angles, and 0.013 Å for groups of atoms expected to be coplanar. No solvent molecules have yet been built into the electron density (Figs. 1 and 2).

**Structure description.** In a space-filling representation of all atoms in the myosin S1 model (Fig. 3), the green, red, and blue segments represent parts of the heavy chain and the yellow and magenta stretches cor-

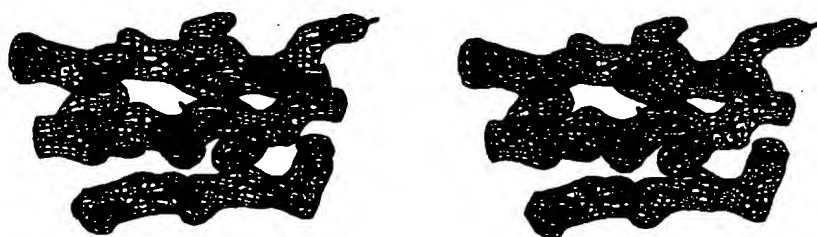


Fig. 2. A stereo view of a representative section of electron density located in the seven-stranded  $\beta$  sheet motif of the heavy chain calculated with SIGMAA coefficients (29). The phases and weights used to calculate the electron density were obtained by combining the information from the heavy atom phases and those derived from the atomic model.

Table 2. Heavy atom derivatives used in the structure determination and their data collection statistics.

Derivative	Conditions*		Method	$R_{\text{sym}}^{\dagger}$	Reflections (no.)	Resolution (Å)	$R_{\text{scale}}^{\ddagger}$	Sites (no.)	Phasing power $^{\S}$
	Concentration (mM)	Time (days)							
Trimethyllead acetate	20	21	Area detector	6.7	13,394	3.5	24.5	4	1.01
KAu(CN) <sub>2</sub>	1	5	Area detector	5.8	18,082	3.5	18.2	6	1.14
K <sub>2</sub> OsO <sub>4</sub> /pyridine	2-20	2	Area detector	6.7	11,804	4.0	24.5	4	1.02
K <sub>3</sub> UO <sub>2</sub> F <sub>6</sub>	3	4	Area detector	6.7	11,688	4.0	19.1	7	1.06
Trimethyllead acetate	20	21	CHESS	11.5	34,498	2.8	28.2	4	1.19
KAu(CN) <sub>2</sub>	1	5	CHESS	9.7	36,339	2.8	17.0	8	1.23
K <sub>2</sub> OsO <sub>4</sub> /pyridine	2-20	2	CHESS	10.0	32,554	2.8	32.2	8	0.99
Cis-Pt(NH <sub>3</sub> ) <sub>2</sub> Cl <sub>2</sub>	2	3	CHESS	10.3	36,108	2.8	21.0	12	1.12
K <sub>3</sub> UO <sub>2</sub> F <sub>6</sub>	3	4	CHESS	10.9	36,419	2.8	22.7	9	0.98
Trimethyllead acetate	15	21	SSRL	13.0	31,667	2.8	27.1	4	1.11
K <sub>3</sub> UO <sub>2</sub> F <sub>6</sub>	2	3	SSRL	11.8	33,043	2.8	22.2	6	0.88

\*The heavy atom derivatives were prepared at 4°C by first slowly transferring the crystals to a synthetic mother liquor composed of 1.5 M ammonium sulfate, 500 mM KCl buffered with 20 mM Pipes at pH 6.7.  $\dagger R_{\text{sym}} = \sum (|I_h| - \langle I_h \rangle) / \sum I_h \times 100$ , where  $I_h$  and  $\langle I_h \rangle$  are the intensities of the individual and mean structure factors.  $\ddagger R_{\text{scale}} = \sum (|F_h| - \langle F_h \rangle) / \sum F_h \times 100$ , where  $F_h$  and  $\langle F_h \rangle$  are the heavy atom and native structure factors.  $\S$ The phasing power is defined as the mean value of the heavy atom structure factor divided by the residual lack-of-closure error.



respond to the essential and regulatory light chains, respectively. As can be seen, the myosin head is highly asymmetric with a length of 165 Å, a width of 65 Å, and a thickness of approximately 40 Å.

Previous knowledge of the organization of the heavy chain in the myosin head was derived from proteolytic studies. Limited tryptic digestion of vertebrate skeletal S1 indicated that the head contained three major regions: a 25-kD NH<sub>2</sub>-terminal nucleotide binding region (32), a central 50-kD segment, and a 20-kD COOH-terminal segment; the last two were shown to bind to

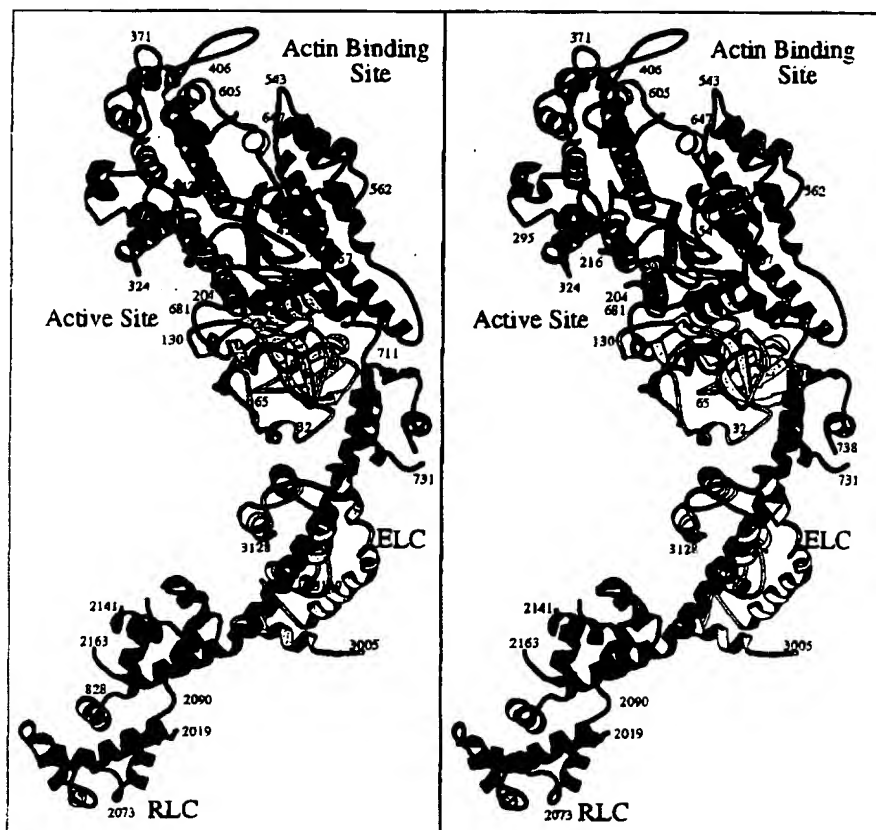
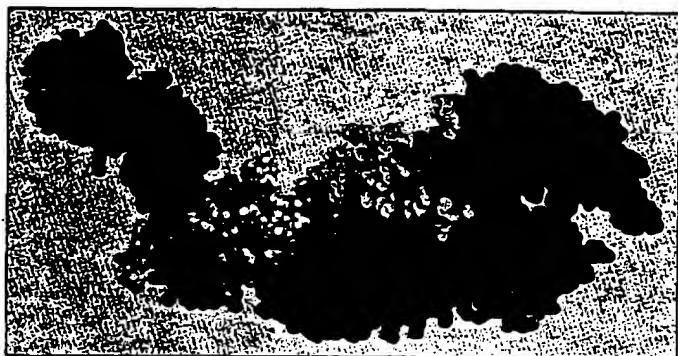
actin (33, 34). These proteolytic segments are displayed in green, red, and blue, respectively (Fig. 3); the light chains abut one another and are wrapped around a single  $\alpha$  helix of the heavy chain but do not overlap to any significant extent.

The secondary structure of the myosin head is dominated by  $\alpha$  helices with approximately 48 percent of the amino acid residues in this conformation (Figs. 4 and 5). One key structural feature is the long (approximately 85 Å)  $\alpha$  helix which extends from the thick part of the head down to the COOH-terminus of the heavy chain.

This  $\alpha$  helix constitutes the light chain binding region of the heavy chain. There is a bend, delineated by amino acid residues Trp<sup>829</sup>, Pro<sup>830</sup>, Trp<sup>831</sup>, and Met<sup>832</sup>, which connects this long  $\alpha$  helix to a short COOH-terminal  $\alpha$  helix of the 95-kD heavy chain fragment. A brief description of the three polypeptide chains constituting the myosin head is given below.

The regulatory light chain is located at the end of the molecule distal from the nucleotide binding site (Figs. 4 and 5). It consists of two domains and shares considerable structural homology with calmodulin and troponin C except that the long connecting helix observed in calmodulin and troponin C is distorted (35, 36). A comparison of the regulatory light chain with calmodulin is shown in Fig. 6A where the eight helices that comprise the two domains have been labeled A through H. The regulatory light chain is arranged such that its NH<sub>2</sub>-terminal domain wraps around the COOH-terminus of the heavy chain between amino acid residues Asn<sup>825</sup> and Leu<sup>842</sup> whereas its COOH-terminal domain interacts with the heavy chain in the region defined by amino acid residues Glu<sup>808</sup> to Val<sup>826</sup>. The interaction of the NH<sub>2</sub>-terminal domain with the heavy chain is stabilized by a cluster of hydrophobic residues including nine phenylalanines, two tryptophans, and one tyrosine.

**Fig. 3.** A space-filling representation of all of the atoms in the current model of myosin S1. The model is oriented such that the actin binding surface is located at the lower right-hand corner. The 25-, 50-, and 20-kD segments of the heavy chain are colored in green, red, and blue, respectively, whereas the essential and regulatory light chains are shown in yellow and magenta, respectively. In this orientation the prominent horizontal cleft that divides the central 50-kD segment of the heavy chain into two domains (upper and lower defined by this orientation) is clearly visible. This figure was prepared with the molecular graphics program MIDAS (67).



**Fig. 4.** A ribbon representation of the entire model for myosin S1. In this and all successive figures, 2000 and 3000 have been added to the residue numbers of the regulatory and essential light chains, respectively, to distinguish these from the heavy chain. Heavy chain residues Asp<sup>4</sup> to Glu<sup>204</sup>, Gly<sup>216</sup> to Tyr<sup>826</sup>, and Gln<sup>847</sup> to Lys<sup>843</sup> are colored in green, red, and blue, respectively. These segments are separated by disordered loops for which no density is evident in the current map. There are two additional segments in the heavy chain for which the density is weak or disordered. These include residues Lys<sup>572</sup> to Lys<sup>574</sup> and Ile<sup>732</sup> to Phe<sup>737</sup>. The A2 isozyme of the essential light chain, shown in yellow, theoretically contains 149 amino acid residues. In the model it extends from residue Asp<sup>5</sup> to Val<sup>149</sup> and contains one ill-defined region that includes residues Leu<sup>50</sup> to Ala<sup>60</sup>. The regulatory light chain, which is colored in magenta, theoretically consists of 166 amino acid residues. In the current model it extends from residue Phe<sup>19</sup> to Lys<sup>183</sup> but is disordered between residues Pro<sup>142</sup> and Asn<sup>147</sup>. In this figure the molecule is oriented perpendicular to its long axis and rotated to view along the active site pocket. A sulfate ion, shown here in a space-filling representation, is located at the base of the pocket. The actin binding surface has been defined as indicated on the figure by the location of the 50- to 20-kD junction (residues Tyr<sup>826</sup> and Gln<sup>847</sup>) and by its interaction with actin (46). Figures 4 to 7 were prepared with the molecular graphics program MOLSCRIPT (62).

tophans, and four methionines. Five of these residues are contributed by the heavy chain. Superposition of the NH<sub>2</sub>-terminal

domains of the regulatory light chain and calmodulin reveals an rms difference in the positions of 59 equivalent residues of only

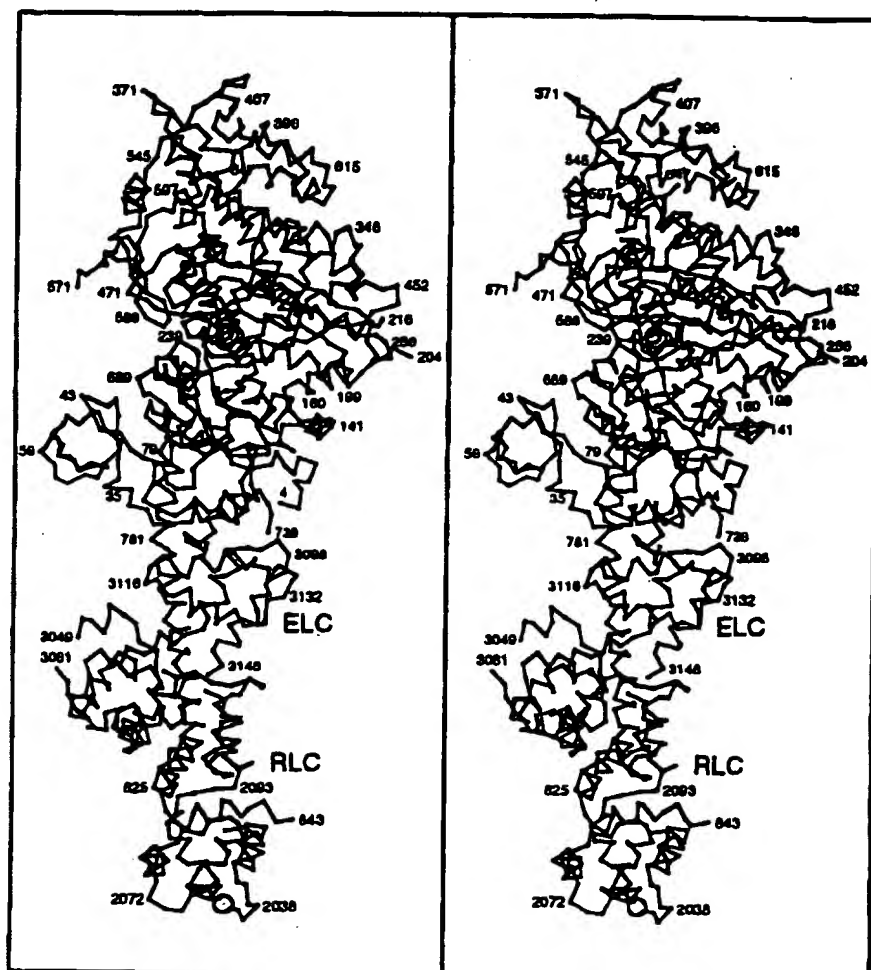


Fig. 5. A stereo  $\alpha$  carbon plot of the entire myosin head in which the view has been rotated 90° with respect to Fig. 4. In this view, the active site pocket is seen as a wide depression. Selected residues have been labeled to allow the path of the chain to be followed and to identify the start and end of the secondary structural elements.

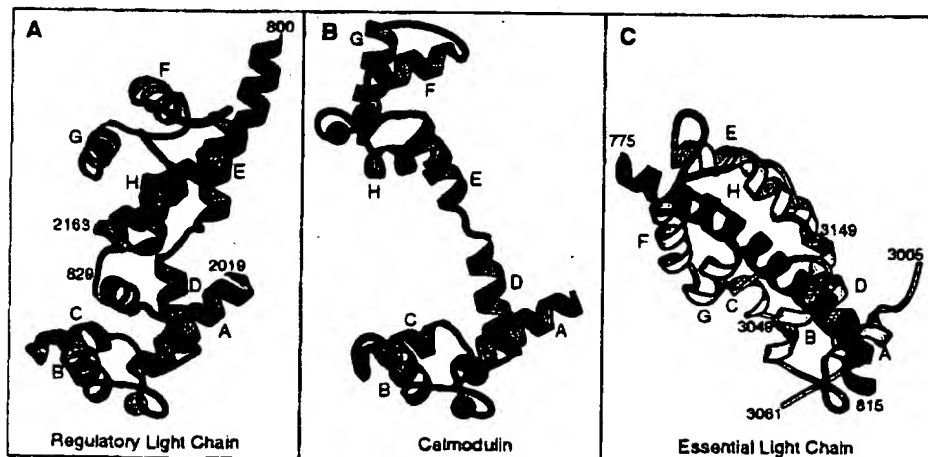


Fig. 6. (A) and (C) show ribbon representations of the regulatory and essential light chains together with the segment of the heavy chain with which they interact. The light chains are oriented such that the NH<sub>2</sub>-terminal domains have the same orientation as calmodulin shown in (B). The coordinates for calmodulin were taken from the Brookhaven Protein Data Bank (file 3CLN) from the structure determined by Cook and co-workers (63).

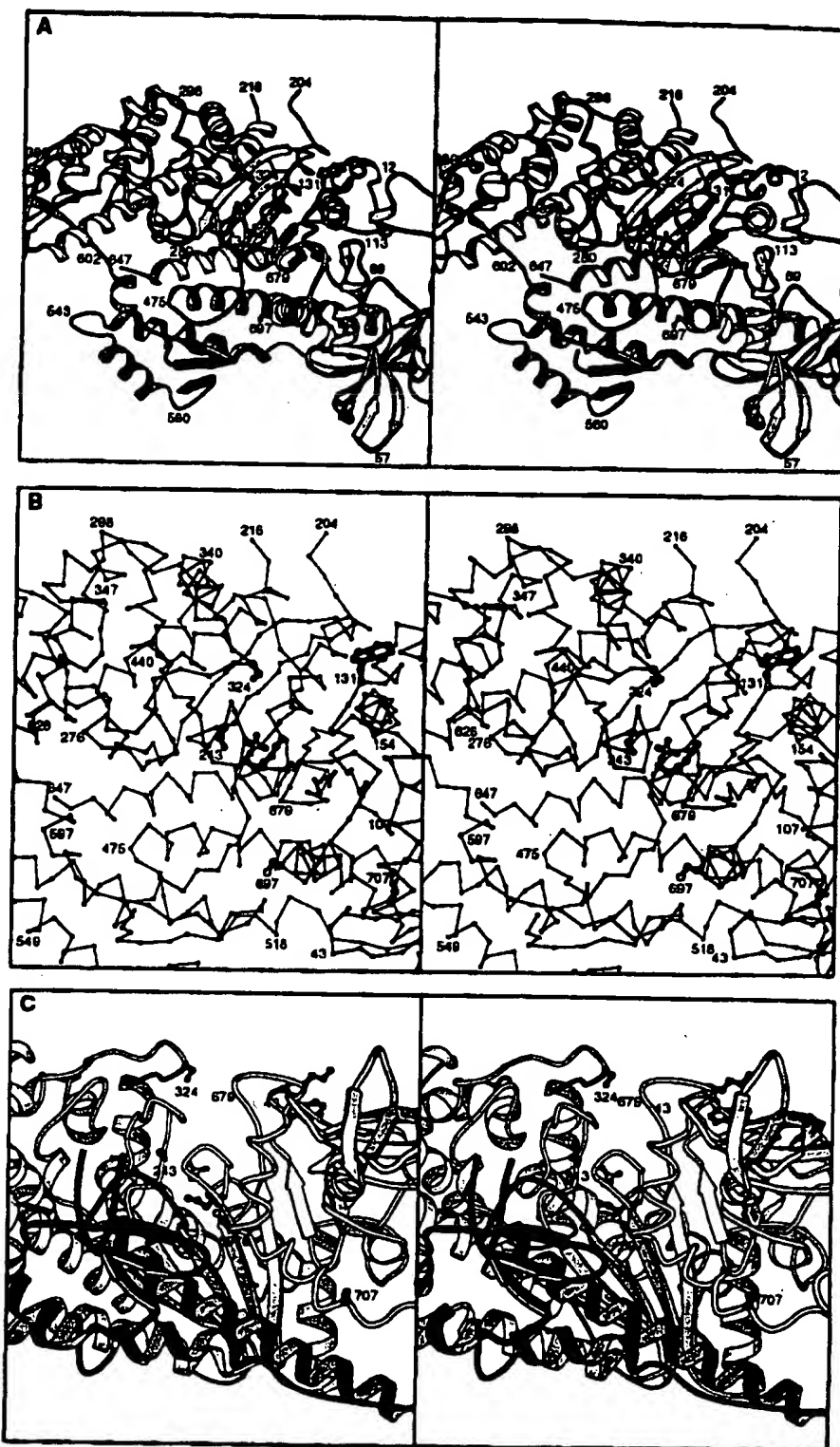
1.3 Å. By contrast the COOH-terminal domain is less similar to the structure observed in calmodulin and is due to a difference in the positions of the F and G helices in the regulatory light chain that have moved to accommodate the heavy chain. In addition, the COOH-terminal domain as a whole has rotated, relative to calmodulin, about the midpoint between the two domains in order to form a tight complex with the heavy chain.

The divalent cation binding site is located in the first helix-loop-helix motif observed in the amino acid sequence and, as indicated above, has a conformation similar to that observed in calmodulin. A divalent cation is clearly evident in the electron density and is most likely Mg<sup>2+</sup> in that this was a minor constituent of the crystallization buffer. In our model, no electron density was observed for the first 18 amino acid residues in the regulatory light chain. This includes Ser<sup>13</sup> and is, by sequence homology to rabbit myosin, the site of phosphorylation by myosin light chain kinase (37). Presumably this portion of the polypeptide chain is flexible in SI and perhaps only plays a functional role when the head is attached to the remainder of the molecule. The observed NH<sub>2</sub>- and COOH-terminal residues of the regulatory light chain lie close to the interface between the two domains.

The essential light chain interacts with the long  $\alpha$  helix of the heavy chain through amino acid residues Leu<sup>783</sup> to Met<sup>806</sup> (Fig. 6C). Likewise, it wraps around the heavy chain  $\alpha$  helix but in a manner different from that observed for the regulatory light chain. Its arrangement resembles that for the interaction of calmodulin with a target peptide from myosin light chain kinase (38). It differs in that the second and third helices in the NH<sub>2</sub>-terminal domain abut the heavy chain with their external surfaces, whereas the corresponding secondary structural elements in calmodulin enclose the respective target peptide. The electron density for this part of the molecule is the least well ordered of the entire map. Indeed, very little of the essential light chain was visible in the original electron density map and only appeared after the phase information from the rest of the molecule was included. This could be due to either lack of isomorphism in the heavy atom derivative phases or conformational flexibility of the polypeptide chain. It is difficult to distinguish between these two possibilities because the crystals contain both classes of essential light chain isoforms. As with the regulatory light chain, the NH<sub>2</sub>- and COOH-terminal residues lie close to the interface between the two domains.

The heavy chain constitutes the entire thick portion of the myosin head and con-

**Fig. 7.** A stereo ribbon and  $\alpha$  carbon plots of the catalytic portion of the myosin head centered on the active site. In (A) and (B) the actin binding face, as defined by the position of the 50- to 20-kD junction, is located on the far side of the molecule. In (C) the molecule has been rotated 90° about the horizontal axis to reveal more clearly the relation between the active site pocket and the reactive cysteine residues. (A) A larger segment of the myosin head that reveals the overall disposition of the secondary structural elements around the nucleotide binding site. The upper domain of the 50-kD segment is shaded in gray whereas the lower domain is shaded in black to emphasize the narrow cleft that divides them. (B) A more detailed view of the residues that form the interface between the upper and lower domains of the 50-kD segment. Marker residues are identified that allow all other residues to be located. In addition, a few of the side chains for the residues that have been implicated to be important in the catalytic mechanism, from amino acid sequence analyses and from chemical studies, have been included. Residues Trp<sup>131</sup> and Ser<sup>324</sup> that have been identified from photolabeling studies lie on opposite sides of the nucleotide binding pocket. (C) The helix connecting the reactive cysteines, Cys<sup>707</sup> and Cys<sup>697</sup>, lies at the base of a cleft at the junction between the lower domain of the 50-kD segment and the NH<sub>2</sub>-terminal 25-kD segment.



tains both the nucleotide binding site and actin binding region. These are located on opposite sides of the protein. This part of the molecule contains a complex arrangement of secondary structural elements centered mainly around a large, mostly parallel, seven-stranded  $\beta$  sheet motif. The topology of this  $\beta$  sheet is such that strands one and six run in the opposite direction to the other five strands. The central strand corresponds to the strand-loop-helix binding motif, which has the sequence GESGAGKT (39), observed both in adenylate kinase and the Ras protein (40). The topology and organization of the heavy chain are described below in terms of the three major tryptic fragments. However, these fragments arise from proteolytic cleavage at flexible loops and do not represent discrete structural domains.

The first observed residue at the NH<sub>2</sub>-terminus of the heavy chain is Asp<sup>4</sup> and is located close to the essential light chain at the approximate center of the entire myosin molecule (Figs. 4 and 5). From here the heavy chain crosses the width of the molecule and forms a small six-stranded antiparallel  $\beta$  sheet motif (Lys<sup>35</sup> to Met<sup>80</sup>), which is fairly independent of the rest of the head and protrudes from the molecule as a whole. The function of this domain is unknown although it does not appear essential for motility in that it is missing in several single-headed myosin I-type molecules (41). The topology of this sheet is similar to that of the Src-homology 3 domain observed in spectrin (42). After this motif, the heavy chain forms three strands of the large  $\beta$  sheet motif that are connected by a series of  $\alpha$  helices. The first two strands

extend from Tyr<sup>116</sup> to Tyr<sup>118</sup> and from Cys<sup>123</sup> to Val<sup>126</sup> and are connected by a  $\beta$  turn. Thereafter there are three short helices prior to the fourth  $\beta$  strand in the sheet that extends from Gln<sup>173</sup> to Gly<sup>179</sup>. The third strand belongs to the COOH-terminal 20-kD fragment of the heavy chain fragment. The fourth or central strand precedes the phosphate binding loop and is followed by a helix,

Lys<sup>185</sup> to Ile<sup>199</sup>, which forms the base of the nucleotide binding pocket. The topology of this loop is essentially identical to that in the Ras protein and adenylate kinase (40). A sulfate ion is embedded in the phosphate binding loop and is located close to the position of the  $\beta$  phosphate observed in the complex between Ap<sub>3</sub>A [P<sup>i</sup>, P<sup>5</sup>, bis-(adenosine-5'-) pentaphosphate] and adeny-



ate kinase (Figs. 4 and 5). It is perhaps not surprising to find a sulfate ion in the nucleotide binding site because ammonium sulfate is a competitive inhibitor of the ATPase activity (43). A break in the electron density is observed between Glu<sup>204</sup> and Gly<sup>216</sup> at the far end of the active site pocket. The missing segment, which contains six charged residues, occurs at the 25- to 50-kD junction and is most likely a constitutively flexible loop.

The 50-kD fragment has a complex topology that can be described as two major domains separated by a long narrow cleft as is evident in the space-filling drawing (Fig. 3). This cleft divides the distal one-third of the myosin head into two regions, which are referred to as the upper and lower domains of the 50-kD segment (Fig. 3).

Electron density for the polypeptide chain resumes at Gly<sup>216</sup> as the start of an  $\alpha$  helix (Leu<sup>218</sup> to Gly<sup>233</sup>). This helix forms part of the nucleotide binding pocket. Thereafter, the chain loops around close to the phosphate binding site and connects up to  $\beta$  strands six and seven of the large  $\beta$  sheet motif that extend from Gly<sup>247</sup> to His<sup>254</sup> and Leu<sup>260</sup> to Tyr<sup>268</sup>, respectively. Strand seven terminates in a domain composed of random coil and several short helices and extending from Glu<sup>271</sup> to Asp<sup>327</sup>. This region is located close to the nucleotide binding site and contains Ser<sup>324</sup> which had been previously identified by photolabeling to be an active site residue (44) (Fig. 7). An  $\alpha$  helix extending from Asp<sup>327</sup> to Ile<sup>340</sup> forms the top of the nucleotide binding pocket. After this domain, the polypeptide chain forms the end of the myosin head through a series of long  $\alpha$  helices. The longest of these is 45 Å in length and extends from Val<sup>419</sup> to Leu<sup>449</sup>. Strand five of the large mixed  $\beta$  sheet follows this helix and extends from Tyr<sup>457</sup> to Ala<sup>465</sup>. This strand terminates in a random coil that drops from the "upper" to "lower" domains of the 50-kD fragment. The midpoint between the upper and lower domains is located close to Gly<sup>466</sup> and occurs in a region of the sequence (Tyr<sup>457</sup> to Gly<sup>516</sup>) that is highly conserved in all myosins (45). Furthermore, the cleft itself contains many individual highly conserved residues that extend into the space between the two domains.

The lower domain is built from several long  $\alpha$  helices (Phe<sup>475</sup> to Lys<sup>505</sup> and Met<sup>517</sup> to Glu<sup>539</sup>), the last of which contains a hydrophobic bulge at Pro<sup>529</sup>. After another helix (Asp<sup>547</sup> to His<sup>558</sup>) there is a three-stranded antiparallel  $\beta$  sheet, which includes residues Asn<sup>564</sup> to Lys<sup>567</sup>, Phe<sup>579</sup> to Val<sup>582</sup>, and Thr<sup>587</sup> to Tyr<sup>590</sup>. The electron density for Lys<sup>572</sup>, Gly<sup>573</sup>, and Lys<sup>574</sup> is very weak, and therefore these residues have been excluded from the model. The segment between Pro<sup>529</sup> and Lys<sup>553</sup> is one component of the actin binding surface as defined by Ray-

ment *et al.* (46). A single segment of random coil (Lys<sup>600</sup> to Leu<sup>603</sup>) passes from the lower domain and across the cleft to form a helix-loop-helix motif on the outer face of the upper 50-kD domain and terminating at Tyr<sup>626</sup>. There is no electron density corresponding to amino acid residues Gly<sup>627</sup> to Phe<sup>646</sup>. This particular stretch contains the second major site of trypsin proteolysis and is the junction between the 50- and 20-kD fragments. The primary sequence in this disordered region contains nine glycine and five lysine residues, suggesting that it may be a flexible region in the molecule. This site is resistant to proteolysis in the actomyosin complex and as such may contribute to the actin binding interface of myosin (33). In addition, this region has also been implicated in actin binding from crosslinking and kinetic studies of proteolytically cleaved protein (34, 47).

Electron density for the polypeptide chain resumes at Gln<sup>647</sup> and proceeds as a long  $\alpha$  helix (Ser<sup>650</sup> to Arg<sup>665</sup>) across the flat face of the molecule toward the light chain binding region and lies between the upper and lower domains of the 50-kD fragment. This helix is part of a highly conserved segment that runs from Leu<sup>658</sup> to Asn<sup>678</sup>. At the end of the helix, the polypeptide chain turns into the center of the molecule and forms the third strand of the mixed  $\beta$  sheet (His<sup>668</sup> to Ile<sup>675</sup>). Thus the major tertiary motif of the head contains contributions from all three of the tryptic fragments. After leaving the  $\beta$  sheet, the polypeptide chain proceeds through the large surface loop defined by Thr<sup>667</sup> to Glu<sup>687</sup>, which caps one end of the nucleotide binding site pocket. Subsequently, the polypeptide chain forms two  $\alpha$  helices lying under the nucleotide binding site and delineated by His<sup>688</sup> to Asn<sup>698</sup> and Val<sup>700</sup> to Arg<sup>708</sup>. This highly conserved segment in the sequence contains the two sulfhydryl groups, Cys<sup>707</sup> and Cys<sup>697</sup>, which are more reactive than the other 11 in the molecule and have been given the names SH1 and SH2, respectively, in the order of their chemical reactivity. These two thiols can be crosslinked by oxidation and a wide variety of bifunctional chemical reagents differing in length from 14 to 3 Å but only in the presence of nucleotide (48). Indeed, formation of a covalent link between these two groups serves to trap Mg<sup>2+</sup>-ADP (adenosine diphosphate) in the active site. Although these reactive sulfhydryls have been thought to reside in a flexible loop, the discovery that these two residues are separated by an  $\alpha$  helix was surprising (Fig. 7C). This is a well-defined region of the electron density map. The fact that the  $\alpha$  carbons of Cys<sup>697</sup> and Cys<sup>707</sup> are approximately 18 Å apart suggests that a rearrangement or conformational change in this area must occur upon nucleotide bind-

ing. This point is further emphasized by the observation that SH1 and SH2 both lie in small clefts that face out toward the solvent on opposite sides of the molecule. The functional significance of this region is also indicated by the very high degree of amino acid sequence conservation in this area of the molecule.

The segment that follows the reactive sulfhydryl groups consists of a small three-stranded antiparallel  $\beta$  sheet that includes residues Arg<sup>714</sup> to Tyr<sup>717</sup>, Tyr<sup>758</sup> to Gly<sup>761</sup>, and Lys<sup>764</sup> to Phe<sup>767</sup>, and is associated with two short helices. This domain is separated from the adjacent NH<sub>2</sub>-terminal domain of the 25-kD fragment of the heavy chain by a distinct cleft and shows a greater association with the COOH-terminal domain of the essential light chain. Thereafter the heavy chain continues as a long  $\alpha$  helix that shows distinct curvature beginning at Leu<sup>771</sup> and ending at Val<sup>826</sup>. There is a decided bend in the course of the polypeptide chain resulting from the Trp<sup>829</sup>, Pro<sup>830</sup>, Trp<sup>831</sup> sequence (Figs. 4 and 5). The heavy chain terminates at residue Lys<sup>843</sup> after a small  $\alpha$  helix that lies nearly at right angles to the preceding long helix.

**Effect of the reductive methylation on the protein structure and function.** One question that must be addressed is the effect, if any, of reductive methylation on the conformation of the protein. An examination of the kinetic properties of modified myosin S1 reveals that the protein is enzymatically active (49). There are changes in the kinetic parameters that are similar to those observed when only the reactive sulfhydryl groups are alkylated (50). The results do not suggest any major changes in the overall conformation of the molecule since these would be expected to abolish its enzymatic activity. Myosin from most sources already contains several post-translationally modified amino acid residues. For example, in chicken skeletal myosin S1, Lys<sup>35</sup> is monomethylated, Lys<sup>130</sup> and Lys<sup>551</sup> are trimethylated, and His<sup>757</sup> contains a 3-N-methylated side chain (27). Although the role of these modified residues is unknown, it has been suggested that methylation of Lys<sup>130</sup> provides a permanent positive charge that may become buried when nucleotide is bound (51). In our structure, Lys<sup>130</sup> is exposed to the solvent at the edge of the nucleotide binding pocket. However, this region of the protein probably rearranges when nucleotide binds because the adjacent Trp<sup>131</sup> is photolabeled by two purine ATP analogues (52).

The structure of methylated lysozyme is essentially identical to that of the native protein (15). From this it is not expected that the folding motifs in myosin S1 will be significantly affected by this treatment. There is, however, the possibility that the relation between the various domains could be altered. Our data reveal that almost all of

the lysine residues are located at the surface and hence would not be expected to influence the structure in any major way. The A2 isozyme of chicken myosin S1 contains 102 lysine residues (27), of which 85 have been built into the model. Of those, 67 are located at the surface of the protein and only 18 participate in salt bridges and can be considered buried. Five of these lysines participate in crystalline contacts. The remaining 17 lysine residues in the A2 isozyme are located in disordered loops; in our structure all except 4 lysine residues are reproducibly modified under conditions where 100 percent dimethylation is expected (Table 1) (15). Thus, the unmodified lysine residues are most likely located in salt bridges where they would be expected to have a higher  $pK_a$ . Mass for the additional methyl groups on the lysine residues is evident in the electron density map for most of the well-ordered side chains. However at this resolution it difficult to categorically decide if a residue has been modified based on the density alone. Even so, it appears that Lys<sup>185</sup>, which resides in the phosphate binding loop, is not modified.

**Active site and possible mechanism for muscle contraction.** The catalytic site of the myosin head was identified by analogy to the phosphate binding loop in both the Ras protein and adenylate kinase and by the position of the amino acid residues previously identified by chemical studies with ATP analogues (52). The nucleotide binding pocket is located on the opposite side of the head from the proposed actin binding site and is in an open conformation (Figs. 4, 5, and 7). The view in Fig. 7 shows the position of the sulfate ion in the phosphate binding loop and a few of the amino acid residues that have been chemically labeled, including Trp<sup>131</sup>, Ser<sup>181</sup>, Ser<sup>243</sup>, and Ser<sup>324</sup> (44, 52, 53). The width of the nucleotide binding pocket at its surface is approximately 15 Å as measured between  $\alpha$  carbons. Since the binding constant of myosin for  $Mg^{2+}$ -ATP is about  $3 \times 10^{11}$  (54) and residues on both sides of the cleft have been photochemically labeled, it is likely that the pocket closes when nucleotides bind in the active site. The pocket is approximately 13 Å wide and 13 Å deep with an angle between the faces of the pocket of  $\sim 40^\circ$ . The base of the cleft is located 90 Å from the COOH-terminus of the myosin head. If the binding face to actin remains essentially stationary, closure of the nucleotide binding cleft could produce a movement at the COOH-terminus of the myosin head of approximately 60 Å. How this rearrangement is actually accomplished cannot be easily predicted from our structure.

The orientation of the molecule in Fig. 5 is rotated such that the actin binding surface is approximately perpendicular to the page (46). Closure of the nucleotide

binding pocket would rotate the COOH-terminal end of the heavy chain that carries the light chains toward the viewer, which is consistent with that expected for the start of the power stroke. From this perspective it appears that a major function of the light chains is to create a longer molecule and hence amplify the conformational changes associated with the active site.

Muscle contraction consists of the cyclic attachment and detachment of the myosin head to the actin filament with the concomitant hydrolysis of ATP. From the extensive kinetic studies on the interaction of myosin with actin (55), a general picture of the sequence of kinetic events occurring during muscle contraction has emerged.

Transient kinetic measurements originally demonstrated that transduction of the chemical energy released by the hydrolysis of ATP into directed mechanical force occurred during product release rather than during the hydrolysis step itself (56). The cycle of events was summarized as follows:  $Mg^{2+}$ -ATP rapidly dissociates the actomyosin complex by binding to the ATPase sites of myosin; free myosin then hydrolyzes ATP and forms a relatively stable myosin-products complex; actin recombines with this complex and dissociates the products, thereby forming the original actin-myosin complex. Presumably, force is generated during the last step. Although this model provided an important conceptual framework for studies of the contractile cycle, it soon became clear that the interactions between myosin, actin, and the substrate and products were more complex (55).

Structural information on the conformational changes that occur during the actomyosin interactions is limited. Addition of ATP causes no significant change in the amount of secondary structure as assessed by circular dichroism (57). The changes observed in tryptophan fluorescence are typical of most enzymes whose active sites are induced to fit around their substrates. However, significant movement within the myosin head must occur during the ATPase activity because of the large change in distance between the two reactive cysteine residues (Cys<sup>707</sup> and Cys<sup>697</sup>) that is induced when nucleotide binds (48, 58). Recent low-angle x-ray scattering studies also suggest a large-scale movement during ATP hydrolysis (59).

In formulating a model for muscle contraction from the structure of myosin S1 presented here, it must be understood that it neither contains nucleotide nor is bound to actin. Most likely the crystal structure is an intermediate between these two extremes, although probably closer to the actin bound state. Preliminary attempts to dock myosin (46) to actin suggest that a better fit to the image reconstructions of S1-decorated actin would be obtained if the long narrow cleft between the upper and lower 50-kD domains were to

close, thus implying that this is an important structural feature of the molecule. In addition, the preliminary fit implies that the actin binding site contains components from both the upper and lower 50-kD domains and the first  $\alpha$  helix from the 20-kD region. From the location of residues Tyr<sup>626</sup> and Gln<sup>647</sup>, the positively charged disordered segment at the 50- to 20-kD junction could readily interact with the negatively charged amino acids at the NH<sub>2</sub>-terminus of actin.

All the current kinetic models for the mechanism of muscle contraction require a change in the binding affinity of myosin for actin when ATP binds to the active site. Although it is difficult to predict how this effect can be communicated to the actin binding site, the structure suggests that this might be generated by changes in the relation between the upper and lower domains of the 50-kD segment prompted by binding of the  $\gamma$  phosphate. Examination of Fig. 7 reveals that the potential binding site for the  $\gamma$  phosphate would be located close to the confluence of the upper and lower domains of the 50-kD region below the current location of the sulfate ion. These observations together with the information from docking myosin onto actin provide the information necessary to formulate a basic structural model for muscle contraction (46).

The three-dimensional model of the myosin S1 presented in this article provides a molecular framework that can be used to address the issues of conformational changes during the contractile cycle and suggests how this molecule functions as a molecular motor. By a combination of molecular biology, in vitro motility assays, and chemical and kinetic studies, it should be possible to test these hypotheses concerning the molecular basis of motility.

Finally, it is appropriate to consider why reductive methylation allows this molecule to crystallize. Examination of the structure reveals that it contains elements of flexibility that might lead to multiple conformations in solution, which in turn might prevent the formation of a crystalline lattice. It is conceivable that reductive methylation serves to stabilize one of these conformations in solution. Alternatively, reductive methylation may serve only to reduce the solubility of the protein.

## REFERENCES AND NOTES

1. R. D. Vale and L. S. B. Goldstein, *Cell* 60, 883 (1990).
2. A. F. Huxley and R. Niedergerke, *Nature* 173, 971 (1954); H. Huxley and J. Hanson, *ibid.* p. 973.
3. S. Lowey, H. S. Slayter, A. G. Weeds, H. Baker, *J. Mol. Biol.* 42, 1 (1969).
4. A. G. Weeds and S. Lowey, *ibid.* 61, 701 (1971).
5. Y. Y. Toyoshima *et al.*, *Nature* 328, 536 (1987).
6. S. S. Margossian, W. F. Stafford III, S. Lowey, *Biochemistry* 20, 2151 (1981).
7. P. D. Wagner and E. Gintler, *Nature* 282, 560 (1981).

8. S. Citi and J. Kendrick-Jones, *BioEssays* 7, 155 (1987).
9. J. S. Sellers, *Curr. Opin. Cell Biol.* 1, 98 (1991).
10. J. H. Collins, *J. Muscle Res. Cell Motil.* 12, 3 (1991).
11. S. Lowey, in *Myology*, A. G. Engel and B. O. Banker, Eds. (McGraw-Hill, New York, 1986), vol. 19, pp. 563-586; P. Vibert and C. Cohen, *J. Muscle Res. Cell Motil.* 9, 296 (1988).
12. A. Elliott and G. Offer, *J. Mol. Biol.* 123, 505 (1978).
13. D. A. Winkelmann, H. Mekeel, I. Rayment, *ibid.* 181, 487 (1985); D. A. Winkelmann, T. S. Baker, I. Rayment, *J. Cell Biol.* 114, 701 (1991).
14. R. H. Rice and G. E. Means, *J. Biol. Chem.* 246, 831 (1971).
15. W. R. Rypniewski, H. M. Holden, I. Rayment, *Biochemistry*, in press.
16. L. Silberstein and S. Lowey, *J. Mol. Biol.* 148, 153 (1981).
17. Y. Nabeshima, Y. Fujii-Kuriyama, M. Muramatsu, K. Ogata, *Nature* 308, 333 (1984).
18. R. Smith, W. R. Rypniewski, I. Rayment, in preparation.
19. I. Rayment and D. A. Winkelmann, *Proc. Natl. Acad. Sci. U.S.A.* 81, 4378 (1984).
20. The data to 3.5 Å resolution were recorded at 4°C on a Siemens X1000D area detector: 13 crystals were used to collect the native data. Most of these crystals were translated to expose a new region after 10 to 11 hours in the x-ray beam such that the data were collected from 35 segments. A total of 94,265 reflections were measured, which reduced to 21,370 unique reflections (Theoretical 24,556) with an  $R_{\text{merge}}$  of 5.3 where
$$R_{\text{merge}} = \frac{\sum (|I_{hi}| - \langle I_{hi} \rangle) / \sum I_{hi}}{\sum I_{hi}} \times 100$$
 $I_{hi}$  and  $\langle I_{hi} \rangle$  are the intensities of the individual and mean structure factors, respectively. These data were recorded with the goal of obtaining a complete, accurate low-resolution x-ray data set that could be used to determine the positions of the heavy atoms in the derivatives. The frame data were processed by the program XDS (64) and scaled with the Fox and Holmes algorithm as implemented by P. Evans in the programs Rotavata and Agrovata (65). The x-ray data between 3.5 and 2.8 Å were recorded on film at the synchrotron sources located at Cornell (CHESS) and Stanford (SSRL). Data were processed with the software developed by M. Rossmann, modified to operate on a VAX (66). The data were merged and scaled with the same software used for the area detector data, except for the inclusion of post-refinement to utilize the partial data (66). A total of 178,986 measurements were recorded on 97 films to yield 36,781 independent reflections in the SSRL native data set with an  $R_{\text{merge}}$  of 9.2. The final native data set consisted of structure factors from 100 to 4.5 Å recorded on the area detector and data from 4.5 to 2.8 Å recorded at SSRL.
21. H. M. Holden and I. Rayment, *Arch. Biochem. Biophys.* 291, 187 (1991).
22. M. G. Rossmann, *Acta Crystallogr.* 13, 221 (1960); T. C. Terwilliger and D. Eisenberg, *Acta Crystallogr. Sect. A* 39, 813 (1983).
23. W. A. Hendrickson and E. E. Lattman, *ibid.* *Acta Crystallogr. Sect. B* 26, 136 (1970).
24. B. C. Wang, *Methods Enzymol.* 115, 90 (1985). The algorithm was written by W. Kabsch (Heidelberg, Germany).
25. M. A. Rould, J. J. Perona, D. Söll, T. A. Steitz, *Science* 246, 1135 (1989).
26. T. A. Jones, *Methods Enzymol.* 115, 157 (1985).
27. T. Maita et al., *J. Biochem.* 110, 75 (1991); G. Matsuda, *Adv. Biophys.* 16, 185 (1983).
28. The size of the side chains observed in the electron density map was matched to the sequence with the program FITSEQ, available from I. Rayment on request.
29. R. J. Read, *Acta Crystallogr. Sect. A* 42, 140 (1986).
30. D. E. Tronrud, L. F. Ten Eyck, B. W. Matthews, *ibid.* 43, 469 (1987).
31. A. T. Brunger, *X-PLOR Manual Version 2.1* (Yale University, New Haven, CT, 1990).
32. L. Sziagyi, M. Balint, F. A. Sreter, J. Gergely, *J. Biochem. Biophys. Res. Commun.* 87, 936 (1979).
33. D. Momet, R. Bertrand, P. Pantel, E. Audemard, R. Kassab, *Biochemistry* 20, 2110 (1981).
34. K. Sutoh, *ibid.* 21, 4800 (1982).
35. Y. S. Babu et al., *Nature* 315, 37 (1985).
36. O. Herzberg and M. N. G. James, *ibid.* 313, 653 (1985).
37. G. Matsuda, Y. Suzuyama, T. Maita, T. Umegane, *FEBS Lett.* 84, 53 (1977).
38. M. Ikura et al., *Science* 256, 632 (1992); W. E. Meador, A. R. Means, F. A. Quiocho, *ibid.* 257, 1251 (1992).
39. Abbreviations for the amino acids residues are A, Ala; C, Cys; D, Asp; E, Glu; F, Phe; G, Gly; H, His; I, Ile; K, Lys; L, Leu; M, Met; N, Asn; P, Pro; Q, Gln; R, Arg; S, Ser; T, Thr; V, Val; W, Trp; and Y, Tyr.
40. C. W. Muller and G. E. Schulz, *J. Mol. Biol.* 224, 159 (1992); E. F. Pai et al., *EMBO J.* 9, 2351 (1990).
41. T. D. Pollard, S. K. Doberstein, H. G. Zoi, *Annu. Rev. Physiol.* 53, 653 (1991).
42. A. Musacchio et al., *Nature* 359, 851 (1992).
43. C. Tesi, T. Barman, F. Travers, *FEBS Lett.* 236, 256 (1988).
44. R. Mahmood, M. Elzinga, R. G. Yount, *Biochemistry* 28, 3989 (1989).
45. H. M. Warrick and J. A. Spudich, *Annu. Rev. Cell Biol.* 3, 379 (1987).
46. I. Rayment et al., *Science* 261, 58 (1993).
47. K. Yamamoto, *J. Mol. Biol.* 217, 229 (1991).
48. M. Burke and E. Reiser, *Biochemistry* 16, 5559 (1977); J. A. Wells and R. G. Yount, *Methods Enzymol.* 85, 93 (1982).
49. H. White and I. Rayment, *Biochemistry*, in press.
50. J. A. Sleep, K. M. Trybus, K. A. Johnson, E. W. Taylor, *J. Muscle Res. Cell Motil.* 2, 373 (1981).
51. Y. Okamoto and R. G. Yount, *Proc. Natl. Acad. Sci. U.S.A.* 82, 1575 (1985).
52. R. G. Yount, C. R. Cremon, J. C. Grammer, B. A. Kerwin, *Philos. Trans. R. Soc. London Ser. B* 336, 55 (1992).
53. C. R. Cremon, J. C. Grammer, R. G. Yount, *J. Biol. Chem.* 264, 6608 (1989); J. C. Grammer and R. G. Yount, *Biophys. J.* 59, 226a (1991).
54. R. S. Goody, W. Hofmann, H. G. Mannherz, *Eur. J. Biochem.* 78, 317 (1977).
55. E. W. Taylor, *CRC Crit. Rev. Biochem.* 6, 103 (1979); R. S. Adelstein and E. Eisenberg, *Annu. Rev. Biochem.* 49, 921 (1980); M. G. Hibberd and D. R. Trentham, *Annu. Rev. Biophys. Biochem.* 15, 119 (1986); M. A. Geeves, *Biochem. J.* 274, 1 (1991).
56. R. W. Lynn and E. W. Taylor, *Biochemistry* 10, 4617 (1971).
57. W. B. Gratzer and S. Lowey, *J. Biol. Chem.* 244, 22 (1969).
58. E. E. Huston, J. C. Grammer, R. G. Yount, *Biochemistry* 27, 8945 (1988).
59. K. Wakabayashi et al., *Science* 258, 443 (1992).
60. Amino acid analyses were performed by L. Mende-Mueller at the Protein and Nucleic Acid Facility, Medical College of Wisconsin, Milwaukee, WI 53226.
61. T. E. Ferrin et al., *J. Mol. Graphics* 6, 13 (1988).
62. P. J. Kraulis, *J. Appl. Cryst.* 24, 946 (1991).
63. Y. S. Babu, C. E. Bugg, W. J. Cook, *J. Mol. Biol.* 204, 191 (1988).
64. W. Kabsch, *J. Appl. Cryst.* 21, 67 (1988); *ibid.*, p. 916.
65. G. C. Fox and K. C. Holmes, *Acta Crystallogr.* 20, 886 (1966).
66. M. G. Rossmann, *Methods Enzymol.* 114, 237 (1985).
67. We thank the co-directors (P. A. Frey, W. W. Cleland, H. Lardy, and G. H. Reed) at the Institute for Enzyme Research for support and discussion, K. Johnson and J. Dewane for technical assistance, and J. Sakon and J. Wedekind for help in the synchrotron data collection and processing. This project was initiated at Brandeis University and continued at the University of Arizona; we thank D. L. D. Casper, J. H. Law, and M. A. Wells at those institutions for their support and encouragement. Supported by NIH grants (I.R., H.M.H., and D.A.W.). I.R. thanks R. Yount for support and encouragement during the long process of solving this structure.

6 April 1993; accepted 4 June 1993

# Structure of the Actin-Myosin Complex and Its Implications for Muscle Contraction

Ivan Rayment,\* Hazel M. Holden, Michael Whittaker, Christopher B. Yohn, Michael Lorenz, Kenneth C. Holmes, Ronald A. Milligan

Muscle contraction consists of a cyclical interaction between myosin and actin driven by the concomitant hydrolysis of adenosine triphosphate (ATP). A model for the rigor complex of F actin and the myosin head was obtained by combining the molecular structures of the individual proteins with the low-resolution electron density maps of the complex derived by cryo-electron microscopy and image analysis. The spatial relation between the ATP binding pocket on myosin and the major contact area on actin suggests a working hypothesis for the crossbridge cycle that is consistent with previous independent structural and biochemical studies.

Muscle contraction occurs when two sets of interdigitating filaments, the thin actin filaments and the thick myosin filaments, slide past one another. A widely accepted theory to explain this process is the cross-bridge hypothesis of muscle contraction whereby sliding is brought about by cross-

bridges that extend from the myosin filament and interact cyclically in a rowing motion with the actin filament as adenosine triphosphate (ATP) is hydrolyzed (1, 2).

The myosin head is an actin-activated adenosine triphosphatase (ATPase). Both solution kinetic studies and fiber experi-